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The art of human-robot interaction: Creative perspectives from design and the arts

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The art of human-robot interaction: Creative perspectives from design and the arts

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EDITORIAL
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Editorial: The Art of Human-Robot Interaction: Creative Perspectives From Design and the Arts

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Keywords: human-robot interaction (HRI), human-computer interaction (HCI), social robotics, collaborative robots, robotic art, creative robotics

Editorial on the Research Topic

The Art of Human-Robot Interaction: Creative Perspectives from Design and the Arts

Advancements in robotics have traditionally been considered the domain of engineering and computer science. However, cross-disciplinary collaborations between the arts and engineering can help drive technical solutions in robotics and fuel innovation in contemporary art (Goldberg, 2001; Herath and Kroos, 2016a; Herath and Kroos, 2016b; Stelarc, 2016). As robotic technologies mature and move beyond research laboratories and the factory floor, there is a greater emphasis and need to understand how to design and implement interactive and collaborative robots in the real world.

User-centred and participatory design methods are well-established in the HCI domain (Wilkinson and De Angeli, 2014), and there is a push to establish similar processes for robot design. Art and design help stimulate this process by involving end-users in the design process and cultivating interdisciplinary approaches for designing and evaluating HRI in the real world. One method for bridging artistic and engineering practices is through workshops that explore diverse disciplinary perspectives to find common ground and identify relevant design principles. Since the early 2010s, many international workshops, forums and programs have explored cross-disciplinary research in robots and art[1] (Smart et al., 2010; St-Onge, 2019). This research topic expands on ideas and discoveries made by this emerging community.

Human-robot co-creation is an enticing entry point to such exploratory work. Santos et al. explore co-creation by introducing a swarm of robot painters, self-organised and augmenting each other's limited painting capabilities. The resulting artworks combine the idea of a single artist with a new form of 'brushstroke' that emerges from swarm cohesion. The authors show how their control algorithm generates coherent renderings even with varying numbers of robots and painting capabilities. On the other hand, Jansen and Sklar present the findings from a workshop to develop a co-creative drawing system using AI. The work involves a multimodal user study with participants from artistic backgrounds. The authors identify potential pitfalls of introducing robots into the creative process, present a prototype, and discuss the lessons learned through exploring the system's shortcomings.

Carter et al. *Lessons From Joint Improvisation Workshops for Musicians and Robotics Engineers* approaches interaction design by exploring musical improvisation to uncover what robot designers and musicians might learn from one another. The authors identify key themes from human musical

[1]https://roboticart.org/

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improvisation that have relevance for robot designers working on machinic improvisation, including spontaneity, learning, and adaptability. The authors consider how these principles might inform design considerations for robot developers. Jansen and Sklar and Carter et al. also incorporate workshops grounded in participatory design, providing sound strategies for thinking about how to work creatively and productively with stakeholders from diverse backgrounds and expertise.

Mixing designers, artists and engineers into workshop activities is also how Sandry et al. approach their research on communicative social robot design. The authors observe a common practice in designing expressive behaviours for robots is to make robots 'cute'. However, for many use cases, this may not be desirable. Therefore, the authors propose 'kawaii' (Japanese) as a design principle, a concept that encompasses 'cute' with playful and surprising personality traits, and provides some valuable insights into the challenges of designing and validating communicative features for social robots.

Gemeinboeck's *The Aesthetics of Encounter: A Relational-Performative Design Approach to Human-Robot Interaction* and Cuan's *OUTPUT: Choreographed and Reconfigured Human and Industrial Robot Bodies Across Artistic Modalities* each represent diverse movement-based perspectives for rethinking and reimagining HRI not as we know it but as it might be. Observing how much HRI research is predicated on design strategies that mimic human features and behavior, the authors contrast the anthropomorphic view of robots, instead emphasising the insights that can emerge from exploring interacting with robots along axes of difference. Gemeinboeck proposes a relational-performative approach to designing robots she terms *bodying-thinging,* an approach that expands the possibilities for imagining how robots are designed and how they might participate socially in encounters with people. Gemeinboeck's work with the Machine Movement Lab (MML) offers alternative pathways that prompt a reconsideration of design for social robots from feminist and movement-based perspectives.

Movement is also the basis for creative inquiry for Cuan's performance, installation, and augmented reality application *OUTPUT*. Her work considers questions of improvisation, embodiment, and mimesis that are central to automating robot motions and HRI. All three approaches invite people to participate directly and creatively to embody a new relationship with industrial robots through movement. The focus is on investigating the contrasts between mechanical and human bodies, and the different kinds of movements they afford.

Critical perspectives from the arts and humanities, such as gender theory and feminist scholarship, are important concepts for HRI research, especially considering the prevalence of gendered robots and the harmful stereotypes that can find their way into robot design and HRI experimental setups. Ladenheim and LaViers' *Babyface: Performance and Installation Art Exploring The Feminine Ideal in Gendered Machines* describes an interactive performance installation that promotes critical reflection on gender stereotypes and sexism in robotics. The article reminds readers of the power of art and aesthetic experiences to help open up critical perspectives on assumptions about technology and interaction between people and machines.

LC et al. present a computer vision-based projection and robotic system in an interactive artwork that explores the idea of self-identification, particularly in children. A user study provides additional perspectives and allows the authors to explore the evolving nature of self-awareness in the age of altered human identity through machine interfaces and interventions. Their preliminary findings also point to possible interventions in healthcare, for example by facilitating social interactions for children with communications disorders like autism. On the other hand, Cooney asks the question of which art-making strategy is most appreciated: exogenous, endogenous or hybrid. He introduces the exogenous strategy as following precisely the human input, while the endogenous one does not consider human input. The user study reaches the conclusion that a hybrid solution is preferable to stimulate creativity and motivate the robotic system's use.

The arts provide an ideal platform for developing robotic solutions and applications that stimulate the public imagination and interest in emerging robot technologies. They also provide a testing ground for studying relevant factors such as intuitive interaction, multimodal communication, trust, design, and usability (Jochum and Goldberg, 2016; St-Onge et al., 2017). The articles in this Research Topic exemplify the kind of novel research outcomes that can result from combining different fields of knowledge.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Interactive Multi-Robot Painting Through Colored Motion Trails

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In this paper, we present a robotic painting system whereby a team of mobile robots equipped with different color paints create pictorial compositions by leaving trails of color as they move throughout a canvas. We envision this system to be used by an external user who can control the concentration of different colors over the painting by specifying density maps associated with the desired colors over the painting domain, which may vary over time. The robots distribute themselves according to such color densities by means of a heterogeneous distributed coverage control paradigm, whereby only those robots equipped with the appropriate paint will track the corresponding color density function. The painting composition therefore arises as the integration of the motion trajectories of the robots, which lay paint as they move throughout the canvas tracking the color density functions. The proposed interactive painting system is evaluated on a team of mobile robots. Different experimental setups in terms of paint capabilities given to the robots highlight the effects and benefits of considering heterogeneous teams when the painting resources are limited.

Keywords: interactive robotic art, robotic swarm, painting, human-swarm interaction, heterogeneous multi-robot teams

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1. INTRODUCTION

The intersection of robots and arts has become an active object of study as both researchers and artists push the boundaries of the traditional conceptions of different forms of art by making robotic agents dance (Nakazawa et al., 2002; LaViers et al., 2014; Bi et al., 2018), create music (Hoffman and Weinberg, 2010), support stage performances (Ackerman, 2014), create paintings (Lindemeier et al., 2013; Tresset and Leymarie, 2013), or become art exhibits by themselves (Dean et al., 2008; Dunstan et al., 2016; Jochum and Goldberg, 2016; Vlachos et al., 2018). On a smaller scale, the artistic possibilities of robotic swarms have also been explored in the context of choreographed movements to music (Ackerman, 2014; Alonso-Mora et al., 2014; Schoellig et al., 2014), emotionally expressive motions (Dietz et al., 2017; Levillain et al., 2018; St.-Onge et al., 2019; Santos and Egerstedt, 2020), or interactive music generation based on the interactions between agents (Albin et al., 2012), among others.

In the context of robotic painting, the focus has been primarily on robotic arms capable of rendering input images according to some aesthetic specifications (Lindemeier et al., 2013; Scalera et al., 2019), or even reproducing scenes from the robot's surroundings—e.g., portraits (Tresset and Leymarie, 2013) or inanimated objects (Kudoh et al., 2009). The production of abstract paintings with similar robotic arm setups remains mostly unexplored, with some exceptions (Schubert, 2017).

While the idea of swarm painting has been substantially investigated in the context of computer generated paintings, where virtual painting agents move inspired by ant behaviors (Aupetit et al., 2003; Greenfield, 2005; Urbano, 2005), the creation of paintings with embodied robotic swarms is lacking. Furthermore, in the existing instances of robotic swarm painting, the generation paradigm is analogous to those employed in simulation: the painting emerges as a result of the agents movement according to some behavioral, preprogrammed controllers (Moura and Ramos, 2002; Moura, 2016). The robotic swarm thus acts in a completely autonomous fashion once deployed, which prevents any interactive influence of the human artist once the creation process has begun. Even in such cases where the human artist participates in the creation of the painting along with the multi-robot system (Chung, 2018), the role of the human artist has been limited to that of a co-creator of the work of art, since they can add strokes to the painting but their actions do not influence the operation of the multi-robot team.

In this paper, we present a multi-robot painting system based on ground robots that lay color trails as they move throughout a canvas, as shown in **Figure 1**. The novelty of this approach lies in the fact that a human user can influence the movement of robots capable of painting specific colors, thus controlling the concentration of certain pigments on different areas of the painting canvas. Inspired by Diaz-Mercado et al. (2015), this human-swarm interaction is formalized through the use of scalar fields—which we refer to as *density functions*—associated with the different colors such that, the higher the color density specified at a particular point, the more attracted the robots equipped with that color will be to that location. Upon the specification of the color densities, the robots move over the canvas by executing a distributed controller that optimally covers such densities taking into account the heterogeneous painting capabilities of robot team (Santos and Egerstedt, 2018; Santos et al., 2018). Thus, the system provides the human user with a high-level way to control the painting behavior of the swarm as a whole, agnostic to the total number of robots in the team or the specific painting capabilities of each of them.

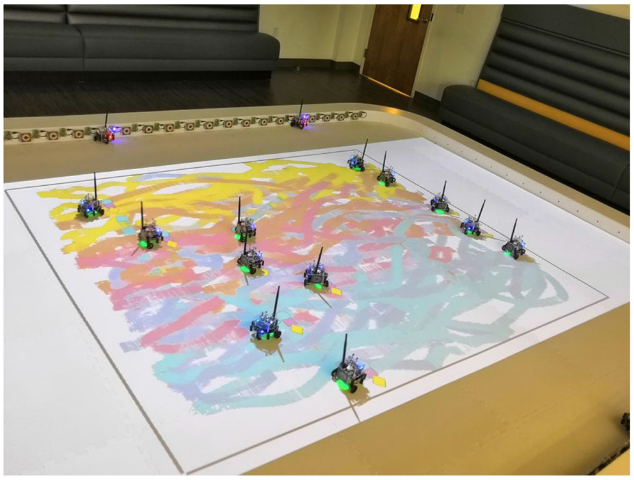

FIGURE 1 | A group of 12 robots generates a painting based on the densities specified by a human user for five different colors: cyan, blue, pink, orange, and yellow. The robots lay colored trails as they move throughout the canvas, distributing themselves according to their individual painting capabilities. The painting arises as a result of the motion trails integrating over time.

The remainder of the paper is organized as follows: In section 2, we formally introduce the problem of coverage control and its extension to heterogeneous robot capabilities, as it enables the human-swarm interaction modality used in this paper. Section 3 elaborates on the generation, based on the user input, of color densities to be tracked by the multi-robot system along with the color selection strategy adopted by each robot for its colored trail. Experiments conducted on a team of differential-drive robots are presented in section 4, where different painting compositions arise as a result of various setups in terms of painting capabilities assigned to the robots. The effects of these heterogeneous resources on the final paintings are analyzed and discussed in section 5, which evaluates the color distribution in the paintings, both through color distances and chromospectroscopy, and includes a statistical analysis that illustrates the consistency of results irrespectively of initial conditions in terms of robot poses. Section 6 concludes the paper.

2. DENSITY-BASED MULTI-ROBOT CONTROL

The interactive multi-robot painting system presented in this paper operates based on the specification of desired concentration of different colors over the painting canvas. As stated in section 1, this color preeminence is encoded through color density functions that the human user can set over the domain to influence the trajectories of the robots and, thus, produce the desired coloring effect. In this section, we recall the formulation of the coverage control problem as it serves as the mathematical backbone for the human-swarm interaction modality considered in this paper.

2.1. Coverage Control

The coverage control problem deals with the question of how to distribute a team of N robots with positions $x_i \in \mathbb{R}^d$, $i \in \{1, \ldots, N\} =: \mathcal{N}$, to optimally cover the environmental features of a domain $D \in \mathbb{R}^d$, $d = 2$ and $d = 3$ for ground and aerial robots, respectively. The question of how well the team is covering a domain is typically asked with respect to a density function, $\phi : D \mapsto [0, \infty)$, that encodes the importance of the points in the domain (Cortes et al., 2004; Bullo et al., 2009). Denoting the aggregate positions of the robots as $x = [x_1^T, \ldots, x_N^T]^T$, a natural way of distributing coverage responsibilities among the team is to let Robot i be in charge of those points closest to it,

$$V_i(x) = \{q \in D \mid \|q - x_i\| \leq \|q - x_j\|, \forall j \in \mathcal{N}\},$$

that is, its Voronoi cell with respect to the Euclidean distance. The quality of coverage of Robot i over its region of dominance can be encoded as,

$$h_i(x) = \int_{V_i(x)} \|x_i - q\|^2 \phi(q)\, dq, \quad (1)$$

where the square of the Euclidean distance between the position of the robot and the points within its region of dominance reflects the degradation of the sensing performance with distance. The performance of the multi-robot team with respect to ϕ can then be encoded through the locational cost in Cortes et al. (2004),

$$\mathcal{H}(x) = \sum_{i=1}^{N} h_i(x) = \sum_{i=1}^{N} \int_{V_i(x)} \|x_i - q\|^2 \phi(q)\, dq, \quad (2)$$

with a lower value of the cost corresponding to a better coverage. A necessary condition for (2) to be minimized is that the position of each robot corresponds to the center of mass of its Voronoi cell (Du et al., 1999), given by

$$C_i(x) = \frac{\int_{V_i(x)} q\phi(q)\, dq}{\int_{V_i(x)} \phi(q)\, dq}.$$

This spatial configuration, referred to as a centroidal Voronoi tessellation, can be achieved by letting the multi-robot team execute the well-known Lloyd's algorithm (Lloyd, 1982), whereby

$$\dot{x}_i = \kappa(C_i(x) - x_i). \quad (3)$$

The power of the locational cost in (2) lies on its ability to influence which areas of the domain the robots should concentrate by specifying a single density function, ϕ, irrespectively of the number of robots in the team. This makes coverage control an attractive paradigm for human-swarm interaction, as introduced in Diaz-Mercado et al. (2015), since a human operator can influence the collective behavior of an arbitrarily large swarm by specifying a single density function, e.g., drawing a shape, tapping, or dragging with the fingers on a tablet-like interface. In this paper, however, we consider a scenario where a human operator can specify multiple density functions associated with the different colors to be painted and, thus, a controller encoding such color heterogeneity must be considered. The following section recalls a formulation of the coverage problem for multi-robot teams with heterogeneous capabilities and a control law that allows the robots to optimally cover a number of different densities.

2.2. Coverage Control for Teams With Heterogeneous Painting Capabilities

The human-swarm interaction modality considered in this paper allows the painter to specify a set of density functions associated with different colors to produce desired concentrations of colors over the canvas. To this end, we recover the heterogeneous coverage control formulation in Santos and Egerstedt (2018). Let $\mathcal{P}$ be the set of paint colors and $\phi_j : D \mapsto [0, \infty)$, $j \in \mathcal{P}$, the family of densities associated with the colors in $\mathcal{P}$ defined over the convex domain, D, i.e., the painting canvas. In practical applications, the availability of paints given to each individual robot may be limited due to payload limitations, resource depletion, or monetary constraints. To this end, let Robot i, $i \in \mathcal{N}$, be equipped with a subset of the paint colors, $p(i) \subset \mathcal{P}$, such that it can paint any of those colors individually or a color that results from their combination. The specifics concerning the color mixing strategy executed by the robots are described in detail in section 3.

Analogously to (1), the quality of coverage performed by Robot i with respect to Color j can be encoded through the locational cost

$$h_i^j(x) = \int_{V_i^j(x)} \|x_i - q\|^2 \phi_j(q)\, dq, \quad (4)$$

where V_i^j is the region of dominance of Robot i with respect to Color j. A natural choice to define the boundaries of V_i^j is for Robot i to consider those robots in the team capable of painting Color j that are closest to it. If we denote as $\mathcal{N}^j$ the set of robots equipped with Color j,

$$\mathcal{N}^j = \{i \in \mathcal{N} \mid j \in p(i) \subset \mathcal{P}\},$$

then the region of dominance of Robot i with respect to Color $j \in p(i)$ is the Voronoi cell in the tessellation whose generators are the robots in $\mathcal{N}^j$,

$$V_i^j(x) = \{q \in D \mid \|x_i - q\| \leq \|x_k - q\|, \forall k \in \mathcal{N}^j\}.$$

Note that, if Robot i is the only robot equipped with Color j, then the robot is in charge of covering the whole canvas, i.e., $V_i^j = D$. Under this partition strategy, as illustrated in **Figure 2**, the area that Robot i is responsible for with respect to Color j, V_i^j, can differ from the region to be monitored with respect to Color k, V_i^k, $j, k \in p(i)$.

With the regions of dominance defined, we can now evaluate the cost in (4). Thus, the overall performance of the team can be evaluated by considering the complete set of robots and color equipments through the *heterogeneous locational cost* formulated in Santos and Egerstedt (2018),

$$\mathcal{H}_{het}(x) = \sum_{j \in \mathcal{P}} \sum_{i \in \mathcal{N}^j} \int_{V_i^j(x)} \|x_i - q\|^2 \phi_j(q)\, dq, \quad (5)$$

with a lower value of the cost corresponding to a better coverage of the domain with respect to the family of color density functions $\phi_j, j \in \mathcal{P}$.

Letting Robot i follow a negative gradient descent of $\mathcal{H}_{het}$ establishes the following control law.

Theorem 1 (Heterogeneous Gradient Descent, Santos and Egerstedt, 2018). *Let Robot i, with planar position x_i, evolve according to the control law $\dot{x}_i = u_i$, where*

$$u_i = \kappa \sum_{j \in p(i)} M_i^j(x)(C_i^j(x) - x_i), \quad (6)$$

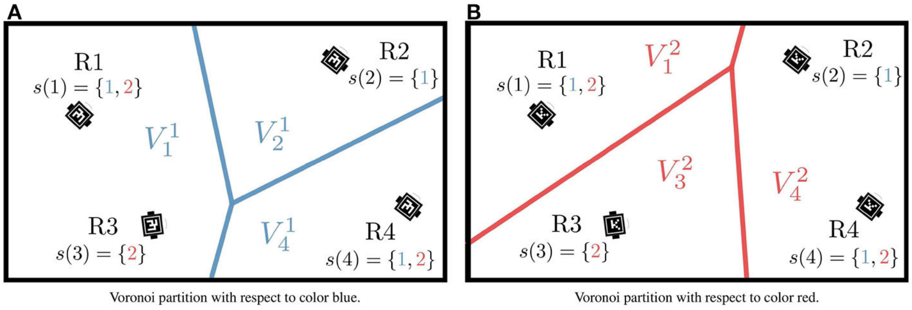

FIGURE 2 | Regions of dominance for four neighboring robots with respect to colors blue (1) **(A)**, and red (2) **(B)**. For each color, the resulting Voronoi cells are generated only by those robots equipped with that painting color. Source: Adapted from Santos and Egerstedt (2018).

with $M_i^j(x)$ and $C_i^j(x)$, respectively, the heterogeneous mass and center of mass of Robot i with respect to Color j, defined as

$$M_i^j(x) = \int_{V_i^j(x)} \phi_j(q)\, dq, \quad C_i^j(x) = \frac{\int_{V_i^j(x)} q\phi_j(q)\, dq}{M_i^j(x)}. \tag{7}$$

Then, as $t \to \infty$, the robots will converge to a critical point of the heterogeneous locational cost in (5) under a positive gain $\kappa > 0$.

Proof: See Santos and Egerstedt (2018).

Therefore, the controller that minimizes the heterogeneous locational cost in (5) makes each robot move according to a weighted sum where each term corresponds with a continuous-time Lloyd descent—analogous to (3)—over a particular color density ϕ_j, weighted by the mass corresponding to that painting capability.

The controller in (6) thus enables an effective human-swarm interaction modality for painting purposes where the human painter only has to specify color density functions for the desired color composition and the controller allows the robots in the team to distribute themselves over the canvas according to their heterogeneous painting capabilities. Note that, while other human-swarm interaction paradigms based on coverage control have considered time-varying densities to model the input provided by an external operator (Diaz-Mercado et al., 2015), in the application considered in this paper heterogeneous formulation of the coverage control problem, while considering static densities, suffices to model the information exchange between the human and the multi-robot system.

3. FROM COVERAGE CONTROL TO PAINTING

In section 2, we established a human-swarm interaction paradigm that allows the user to influence the team of robots so that they distribute themselves throughout the canvas according to a desired distribution of color and their painting capabilities. But how is the painting actually created? In this section, we present a strategy that allows each robot to choose the proportion in which the colors available in its equipment should be mixed in order to produce paintings that reflect, to the extent possible, the distributions of color specified by the user.

The multi-robot system considered in this paper is conceived to create a painting by means of each robot leaving a trail of color as it moves over a white canvas. While the paintings presented in section 4 do not use physical paint but, rather, projected trails over the robot testbed, the objective of this section is to present a color model that both allows the robots to produce a wide range of colors with minimal painting equipment and that closely reflects how the color mixing would occur in a scenario where physical paint were to be employed. To this end, in order to represent a realistic scenario where robots lay physical paint over a canvas, we use the subtractive color mixing model (see Berns, 2000 for an extensive discussion in color mixing), which describes how dyes and inks are to be combined over a white background to absorb different wavelengths of white light to create different colors. In this model, the primary colors that act as a basis to generate all the other color combinations are cyan, magenta, and yellow (CMY).

The advantage of using a simple model like CMY is two-fold. Firstly, one can specify the desired presence of an arbitrary color in the canvas by defining in which proportion these should mix at each point and, secondly, the multi-robot system as a collective can generate a wide variety of colors being equipped with just cyan, magenta and yellow paint, i.e., $\mathcal{P} = \{C, M, Y\}$ in the heterogeneous multi-robot control strategy in section 2.2. The first aspect reduces the interaction complexity between the human and the multi-robot system: the painter can specify a desired set of colors $\mathcal{C}$ throughout the canvas by defining the CMY representation of each color $\beta \in \mathcal{C}$ as $[\beta_C, \beta_M, \beta_Y], \beta_j \in [0, 1], j \in \mathcal{P}$, and its density function over the canvas $\phi_\beta(q), q \in D$. Note that a color specified in the RGB color model (red, green, and blue), represented by the triple $[\beta_R, \beta_G, \beta_B]$, can be directly converted to the CMY representation by subtracting the RGB values from 1, i.e., $[\beta_C, \beta_M, \beta_Y] = 1 - [\beta_R, \beta_G, \beta_B]$. Given that the painting capabilities of the multi-robot system are given by $\mathcal{P} = \{C, M, Y\}$, the densities that the robots are to cover according to the heterogeneous coverage formulation in section 2.2 can be obtained as,

$$\phi_j(q) = \bigoplus_{\beta \in \mathcal{C}} \beta_j \phi_\beta(q), \quad j \in \mathcal{P},$$

where $\oplus$ is an appropriately chosen composition operator. The choice of composition operator reflects how the densities associated with the different colors should be combined in order to compute the overall density function associated with each CMY primary color. For example, one way to combine the density functions is to compute the maximum value at each point,

$$\phi_j(q) = \max_{\beta \in \mathcal{C}} \beta_j \phi_\beta(q), \quad j \in \mathcal{P}.$$

The question remaining is how a robot should combine its available pigments in its color trail to reflect the desired color density functions. The formulation of the heterogeneous locational cost in (5) implies that Robot i is in charge of covering Color j within the region dominance V_i^j and of covering Color k within V_i^k, $j, k \in p(i) \subset \mathcal{P}$. However, depending on the values of the densities ϕ_j and ϕ_k within these Voronoi cells, the ratio between the corresponding coverage responsibilities may be unbalanced. In fact, such responsibilities are reflected naturally through the heterogeneous mass, $M_i^j(x)$, defined in (7). Let us denote as $[\alpha_i^C, \alpha_i^M, \alpha_i^Y]$, $\alpha_i^j \in [0,1]$, $\alpha_i^C + \alpha_i^M + \alpha_i^Y = 1$, the color proportion in the CMY basis to be used by Robot i in its paint trail. Then, a color mixing strategy that reflects the coverage responsibilities of Robot i can be given by,

$$\alpha_i^j = \frac{M_i^j(x)}{\sum_{k \in p(i)} M_i^k(x)}, \quad j \in p(i) \subset \mathcal{P}. \tag{8}$$

Note that, when $M_i^j(x) = 0, \forall j \in p(i) \subset \mathcal{P}$, the robot is not covering any density and, thus, $\alpha_i^j, j \in \mathcal{P}$, can be undefined.

Figure 3 illustrates the operation of this painting mechanism for three different density color specifications. Firstly, the mechanism is simulated for a robot equipped with all three colors—cyan (C), magenta (M), and yellow (Y)—in **Figures 3A,C,E**. As seen, the robot lays a cyan trail as it moves to optimally cover a single cyan density function in **Figure 3A**. In **Figure 3C**, two different density functions are specified, one magenta and one yellow, and the robot lays down a trail whose color is a combination of both paints. Finally, in **Figure 3E**, the robot is tasked to cover a density that is a combination of the CMY colors. Since the robot is equipped with all three colors, the trail on the canvas exactly replicates the colors desired by the user.

For the same input density specifications, **Figures 3B,D,F** illustrate the trails generated by a team of three robots equipped with different subsets of the color capabilities. As seen, the color of the individual robot trails evolve as a function of the robot's equipment, the equipments of its neighbors, and the specified input density functions. A simulation depicting the operation of this painting mechanism can be found in the video included in the **Supplementary Materials**.

4. EXPERIMENTAL RESULTS WITH PROJECTED TRAILS

The proposed multi-robot painting system is implemented on the Robotarium, a remotely accessible swarm robotics testbed at the Georgia Institute of Technology (Wilson et al., 2020). The experiments, uploaded via web, are remotely executed on a team of up to 20 custom-made differential-drive robots. On each iteration, run at a maximum rate of 120 Hz, the Robotarium provides the poses of the robots, tracked by a motion capture system, and allows the control program to specify the linear and angular velocities to be executed by each robot in the team. An overhead projector affords the visualization of time-varying images onto the test bed during the execution of the experiments. The data is made available to the user once the experiment is finalized.

The human-swarm interaction paradigm for color density coverage presented in section 2 and the trail color mixing strategy from section 3 are illustrated experimentally on a team of 12 robots over a 2.4 × 2m canvas. The robots lay trails of color as they cover a set of user-defined color density functions according to the control law in (6), where $\kappa = 1$ for all the experiments and the single integrator dynamics $u_i, i \in \mathcal{N}$ are converted into linear and angular velocities executable by the robots using the near-identity diffeomorphism from Olfati-Saber (2002), a functionality available in the Robotarium libraries. In order to study how the limited availability of painting resources affects the resulting painting, for the same painting task, nine different experimental setups in terms of paint equipment assigned to the multi-robot team are considered. While no physical paint is used in the experiments included in this paper, the effectiveness of the proposed painting system is illustrated by visualizing the robots' motion trails over the canvas with an overhead projector.

The experiment considers a scenario where the multi-robot team has to simultaneously cover a total of six different color density functions over a time horizon of 300 s. These density functions aim to represent commands that would be interactively generated by the user, who would be observing the painting being generated and could modify the commands for the color densities according to his or her artistic intentions. Note that, in this paper, these time-varying density functions are common to all the experiments and simulations included in sections 4, 5 to allow the evaluation of the paintings as a function of the equipment setups in **Table 2**. In an interactive scenario, the density commands are to be generated in real time by the user, by means of a tablet-like interface, for example. In this experiment, the color density functions involved are of the form,

$$\phi_\beta(q) = \frac{K}{2\pi\sigma_x\sigma_y} \exp\left(-\frac{(q_x - \bar{\mu}_x)^2 + (q_y - \bar{\mu}_y)^2}{2\sigma_x^2\sigma_y^2}\right), \tag{9}$$

with $\beta \in \{1, \ldots, 6\} = \mathcal{C}$, $q = [q_x, q_y]^{\mathrm{T}} \in D$. The color associated with each density as well as its parameters are specified in **Table 1**, and $\bar{\mu}_x$ and $\bar{\mu}_y$ are given by

$$\bar{\mu}_x = \mu_x - A_x \sin(2\pi f_x t),$$
$$\bar{\mu}_y = \mu_y - A_y \sin(2\pi f_y t).$$

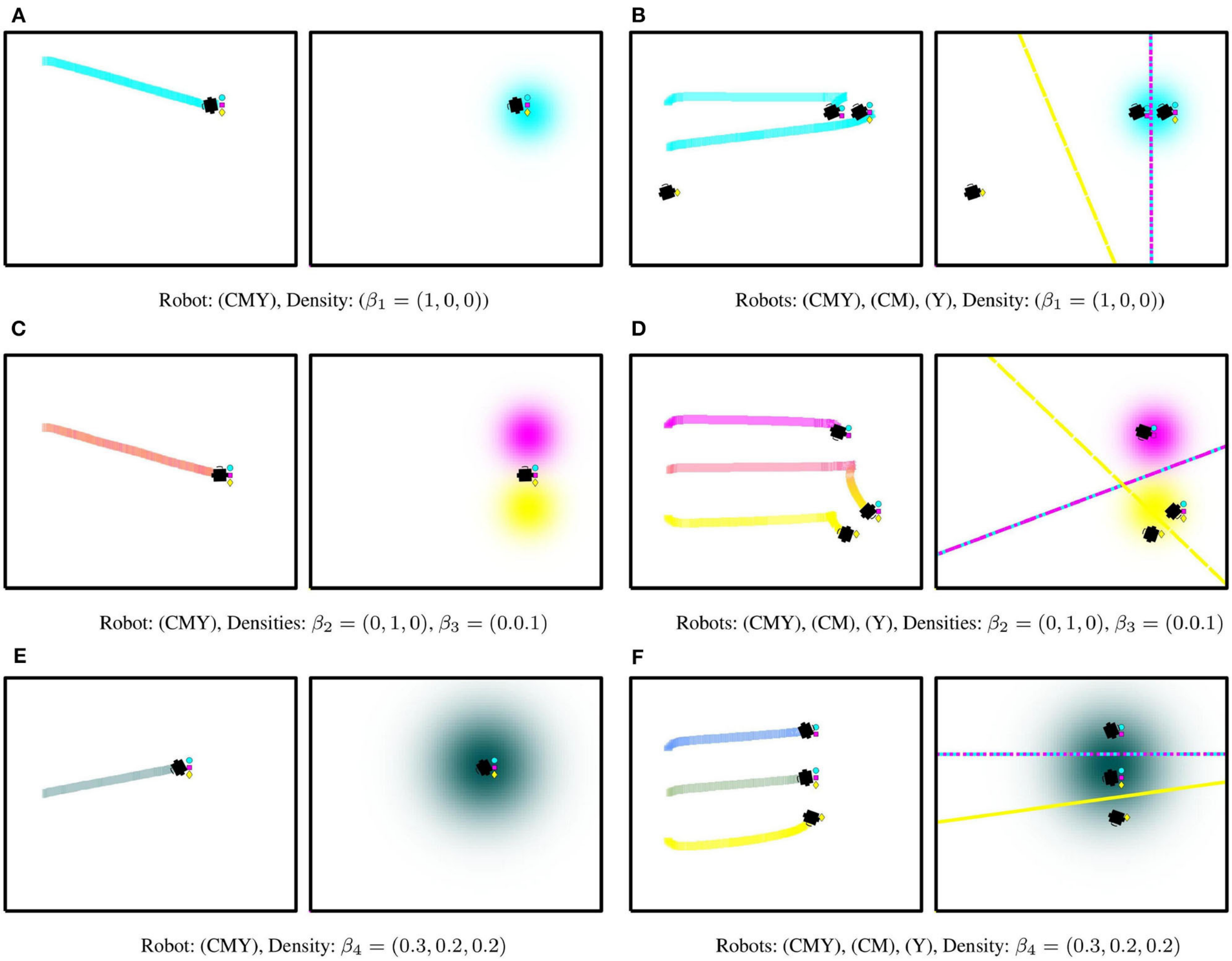

FIGURE 3 | Painting mechanism based on heterogeneous coverage control. Each subfigure shows the color trails laid by the robots (left) as they move to optimally cover a user-specified color density function (right) by executing the controller in (6). The symbols located to the right of the robot indicate its painting capabilities. **(A,C,E)** Show the operation of the painting mechanism in section 3 for a single robot equipped with all three colors, i.e., cyan (C), magenta (M), and yellow (Y), thus capable of producing all color combinations in the CMY basis. In **(A)**, the robot lays a cyan trail according to the density color specification β_1. The robot equally mixes magenta and yellow in **(C)** according to the color mixing strategy in (8), producing a color in between the two density color specifications, β_2 and β_3. Finally, in **(E)**, the robot exactly replicates the color specified by β_4. On the other hand, **(B,D,F)** depict the operation of the painting mechanism with a team of 3 robots, where the Voronoi cells (color coded according to the CMY basis) are shown on the density subfigures.

TABLE 1 | Experimental parameters associated with the user-specified color density functions.

β	Color	β_C	β_M	β_Y	K	μ_x	μ_y	σ_x	σ_y	A_x	A_y	f_x	f_y
1	Yellow	0.0000	0.0863	0.5569	60	0	0.8	0.22	0.22	1.1	0.1	1/40	0
2	Orange	0.0000	0.3529	0.5569	40	0	0.4	0.22	0.22	1.1	0.1	1/37	2/15
3	Pink	0.0549	0.5529	0.3451	40	0	0	0.22	0.22	1.1	0.1	1/35	0
4	Blue	0.4314	0.3098	0.1373	60	0	−0.4	0.22	0.22	1.1	0.1	1/33	2/15
5	Cyan	0.9686	0.0353	0.0275	40	0	−0.8	0.22	0.22	1.1	0.1	1/30	0
6	Yellow Sun	0	0	1	60	0.5	0.3	0.125	0.125	0.1	0.1	1/5	1/5

Figure 4 illustrates the evolution of the painting for a specific equipment setup as the robots move to cover these densities at $t = 100$s and $t = 300$s.

The multi-robot painting strategy is evaluated under a series of painting equipment setups to assess the differences that result from the heterogeneity of the team, which can be motivated by the scarcity or depletion of painting resources or by a design choice of the human user, for example. **Table 2** outlines the color painting capabilities available to each of the robots in the different experimental setups. The paintings which result from five of these

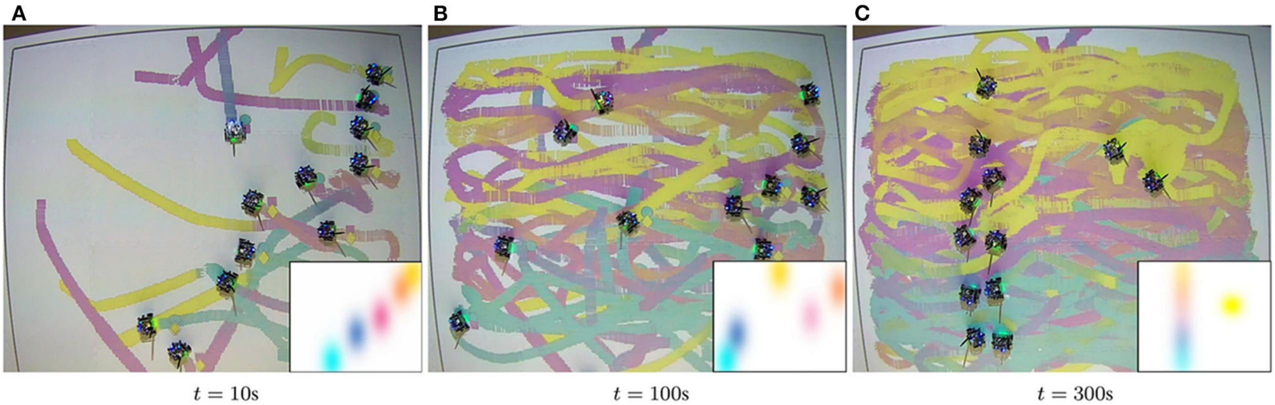

FIGURE 4 | Evolution of the painting according to the density parameters in **Table 1**, for the Setup 3 given as in **Table 2**. The robots distribute themselves over the domain in order to track the density functions as they evolve through the canvas. In each snapshot, the densities that the multi-robot team is tracking at that specific point in time are depicted in the bottom right corner of the image. The color distribution of the color trails reflects the colors specified for the density functions within the painting capabilities of the robots. Even though none of the robots is equipped with the complete CMY equipment and, thus, cannot reproduce exactly the colors specified by the user, the integration of the colors over time produce a result that is close to the user's density specification.

TABLE 2 | Paint equipment for the different experimental setups.

Setup		Paint equipment																Heterogeneity	
ID	ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total	Sunset	8-bit RGB
	C	×	×	×	×	×	×	×	×	×	×	×	×				12		
1	M	×	×	×	×	×	×	×	×	×	×	×	×				12	0	0
	Y	×	×	×	×	×	×	×	×	×	×	×	×				12		
	C	×			×		×	×	×	×	×	×	×	×	×	×	12		
2	M		×		×	×		×	×	×	×	×	×	×	×	×	12	0.2786	0.2680
	Y			×		×	×	×	×	×	×	×	×	×	×	×	12		
	C	×	×			×	×	×	×			×	×				8		
3	M	×	×	×	×			×	×	×	×						8	0.3060	0.2963
	Y			×	×	×	×			×	×	×	×				8		
	C	×		×	×	×		×		×	×	×	×				9		
4	M		×	×		×	×	×	×		×	×	×				9	0.3340	0.3121
	C		×	×		×	×		×	×	×	×	×				9		
	C	×			×		×	×	×	×	×	×	×				9		
5	M		×		×	×		×	×	×	×	×	×				9	0.3921	0.3783
	Y			×		×	×	×	×	×	×	×	×				9		
	C	×	×					×	×	×	×	×	×				8		
6	M			×	×			×	×	×	×	×	×				8	0.4488	0.4398
	Y					×	×	×	×	×	×	×	×				8		
	C	×			×	×			×	×	×	×	×				8		
7	M		×		×	×	×	×			×	×	×				8	0.5686	0.5498
	Y			×			×	×	×	×	×	×	×				8		
	C	×	×	×							×	×	×				6		
8	M				×	×	×				×	×	×				6	0.6904	0.6835
	Y							×	×	×	×	×	×				6		
	C	×	×					×	×			×	×				6		
9	M			×	×			×	×	×	×						6	0.8148	0.8004
	Y					×	×			×	×	×	×				6		

configurations (the ones with an odd setup ID) are shown in **Figure 5**. The generative process for the paintings in **Figure 5** is illustrated in the video included in the **Supplementary Materials**. Note that all these experiments where run with identical initial conditions in terms of robot poses, according to the identifiers in **Table 2**. For the purpose of benchmarking, a

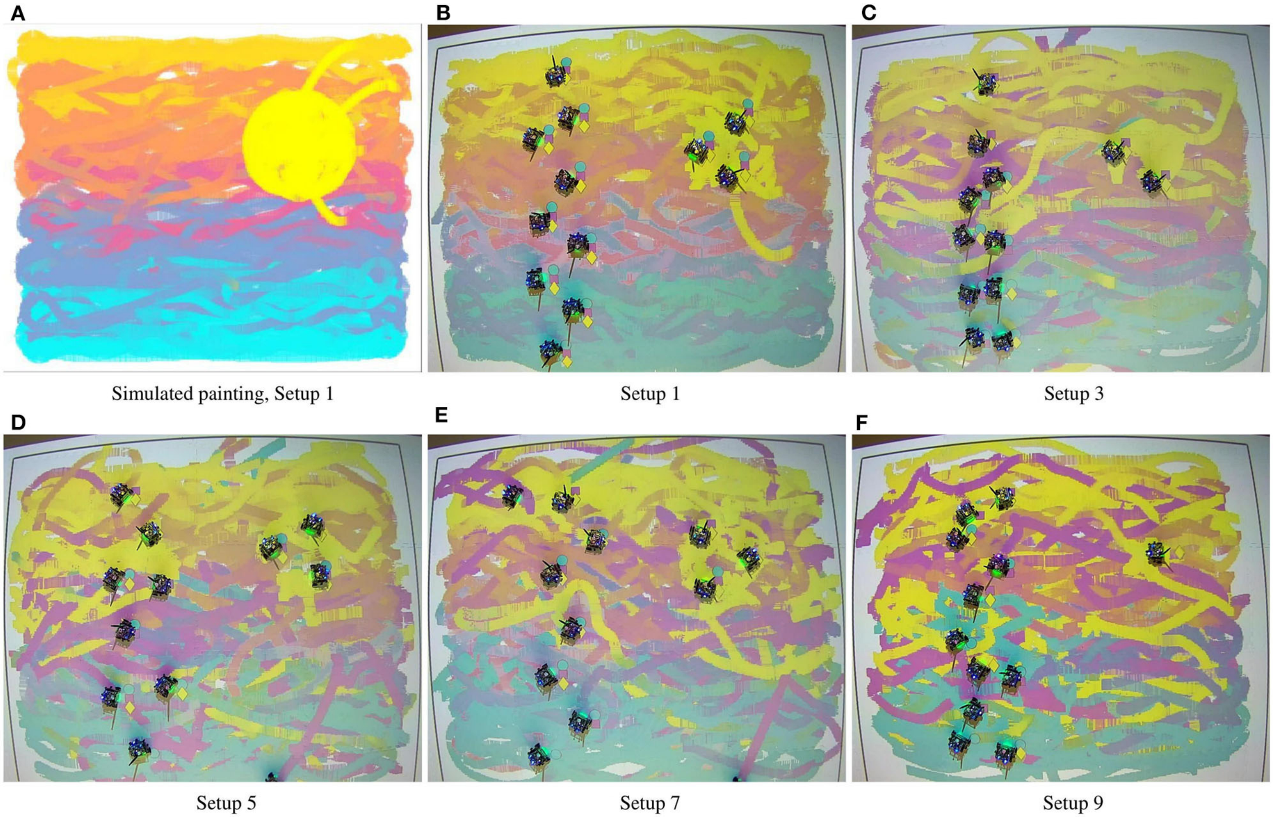

FIGURE 5 | Paintings generated for the densities in (9), with the team of 12 robots in their final positions. **(A)** Corresponds to a simulated painting and it is used for benchmarking. According to the painting equipment setups in **Table 2** we can see how, as the robots in the team are equipped with more painting capabilities, the color gradients become smoother and more similar to the ideal outcome.

simulated painting is generated for painting setup 1, i.e., with a homogeneous equipment capable of reproducing any color. This simulated painting is created under the same heterogeneous density coverage control and color mixing strategies as in the robotic experiments, but considering unicycle dynamics without actuator limits or saturation and with no communication delays (**Figure 5A**). Given the paintings in **Figures 5B–F**, we can observe how the closest color distribution to the simulated painting is achieved in **Figure 5B**, which corresponds to the case where all the robots have all the painting capabilities—i.e., the team is homogeneous—and, thus, can reproduce any combination of colors in the CMY basis.

It is interesting to note the significant changes in the characteristics of the painting for different equipment configurations of the robots. For equipment setups 3, 5, 7, and 9, where some robots—or all—are not equipped with all the color paints, the corresponding paintings do not show as smooth color gradients as the one in **Figure 5B**. However, the distribution of color for these paint setups still qualitatively reflects the color specification given by the densities in **Table 1**. Even in the extreme case of Equipment 9 (see **Figure 5F**), where none of the robots is equipped with all CMY paints—in fact, half of the robots only have one paint and the other half have pairwise combinations—the robot team still renders a painting that, while presenting colors with less smooth blending than the other setups, still represents the color distribution specified by the densities in **Table 1**. For Setups 3 and 7, the team has the same total number of CMY painting capabilities but the distribution is different among the team members: in Setup 3 none of the robots are equipped with the three colors, while in Setup 7 there are some individuals that can paint any CMY combination and others can paint only one color. Observing the **Figures 5C,E**, while the resulting colors are less vibrant for the equipment in Setup 3, there seems to be a smoother blending between them along with the vertical axis. Setup 7 produces a painting where overall the colors are more faithful to the ideal outcome presented in **Figure 5A**, but that also contain stronger trails corresponding to the pure primary colors appear throughout the painting. If we compare **Figures 5D,E** we can see how, by adding a small amount of painting capabilities to the system, the color gradients are progressively smoothed. This observation suggests to further analyze the variations that appear on the paintings as a function of the heterogeneous equipment configurations of the different setups. This will be the focus of the next section.

5. ANALYSIS AND DISCUSSION

As described in section 1, the robotic painting system developed in this paper generates illustrations via an interaction between the color density functions specified by the user and the different color equipment present on the robots. In particular, the different equipments not only affect the color trails left by the robots, but also affect their motion as they track the density functions corresponding to their equipment. While **Figure 5** qualitatively demonstrates how the nature of the painting varies with different equipment setups, this section presents a quantitative analysis of the variations among paintings resulting from different equipment setups. We also analyze the reproducibility characteristics of the multi-robot painting system, by investigating how paintings vary among different realizations using the same equipment setups.

Let S denote the number of distinct equipment setups of the robots in the team—where each unique configuration denotes a robot *species*. We denote $s_\iota \in [0, 1]$ as the probability that a randomly chosen agent belongs to species ι, $\iota \in \mathcal{S} = \{1, \ldots, S\}$, such that

$$\sum_{\iota=1}^{S} s_\iota = 1, \quad \text{and } s = [s_1, \ldots, s_S]^{\mathrm{T}}.$$

For each equipment setup in **Table 2**, these probabilities can be calculated as a function of how many agents are equipped with each subset of the paint colors.

We adopt the characterization developed in Twu et al. (2014), and quantify the heterogeneity of a multi-robot team as,

$$H(s) = E(s)Q(s), \tag{10}$$

where $E(s)$ represents the *complexity* and $Q(s)$, the *disparity* within the multi-robot system for a given experimental setup, s. More specifically, $E(s)$ can be modeled as the *entropy* of the multi-agent system,

$$E(s) = -\sum_{\iota=1}^{S} s_\iota \log(s_\iota),$$

and $Q(s)$ is the *Rao's Quadratic Entropy*,

$$Q(s) = \sum_{\iota=1}^{S} \sum_{\kappa=1}^{S} s_\iota s_\kappa \delta(\iota, \kappa)^2, \tag{11}$$

with $\delta : \mathcal{S} \times \mathcal{S} \mapsto \mathbb{R}_+$ a metric distance between species of robots. More specifically, δ represents the differences between the abilities of various species *in the context of performing a particular*

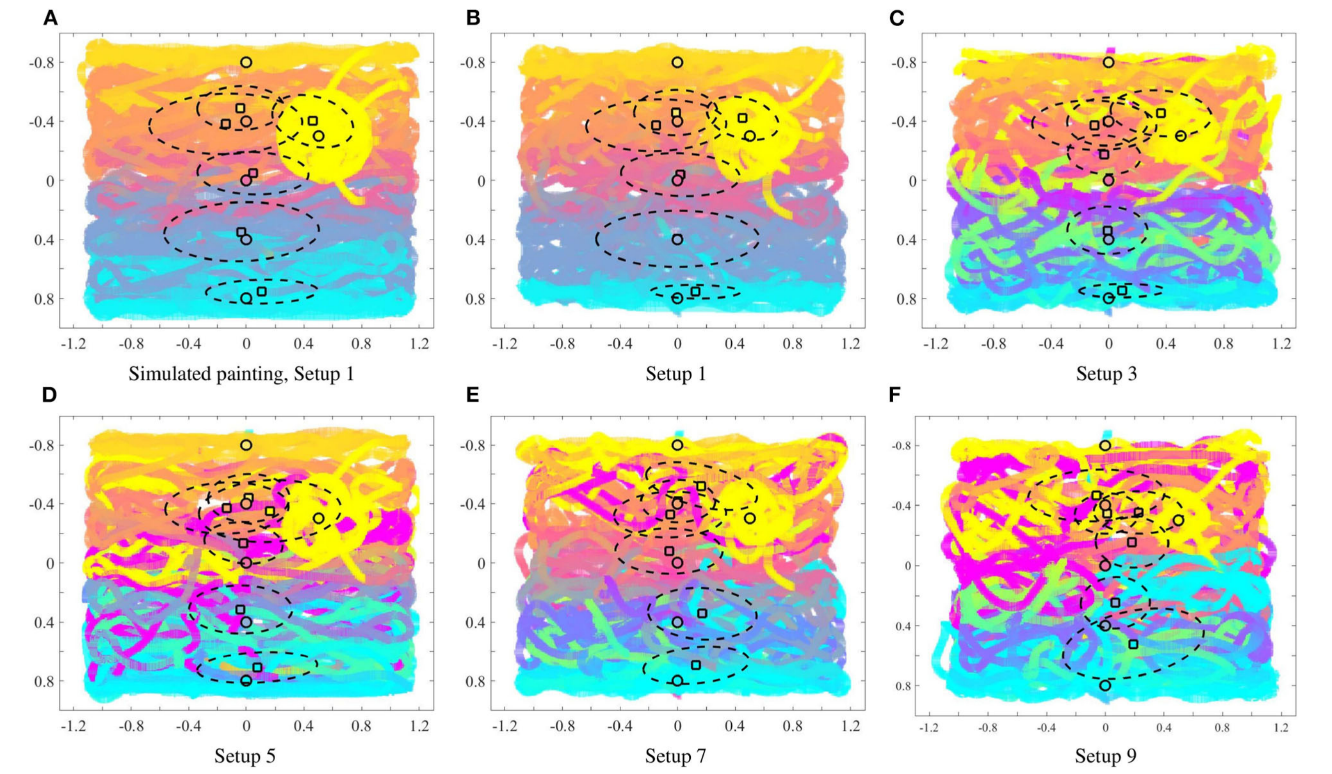

FIGURE 6 | For each input color (given in **Table 1**): mean of the input density function (circle), and center of mass of the resulting color according to (13) (square). The dotted lines depict the covariance ellipse according to (14). As seen the heterogeneity of the multi-robot team [as defined in (10)] impacts how far the colors are painted from the location of the input, as given by the user.

task. For example, if we have three robots, one belonging to species s_5 ($p(s_5) = \{C\}$) and two belonging to species s_8 ($p(s_8) = \{C, M, Y\}$) and we have to paint only cyan, then the distance between agents should be zero, since all of them can perform the same task. However, if the task were to paint a combination of yellow and magenta, then the species s_5 could not contribute to that task and, therefore, $\delta > 0$.

Similar to Twu et al. (2014), we formalize this idea by introducing a task space, represented by the tuple (T, γ) where T denotes the set of tasks, and $\gamma : T \mapsto \mathbb{R}_+$ represents an associated weight function. In this paper, the set of tasks T simply correspond to the different colors specified by the user, as shown in **Table 1**. Consequently, a task $t^j_\beta \in T$ corresponds to the component j, $j \in \{C, M, Y\}$, of color input $\beta \in \mathcal{C}$. The corresponding weight functions for the tasks are calculated as,

$$\gamma(t^j_\beta) = \frac{\beta_j}{\sum_{\tilde{\beta}\in\mathcal{C}} \sum_{k\in\mathcal{P}} \tilde{\beta}_k}.$$

With this task-space, the task-map, $\omega : \mathcal{S} \mapsto 2^T$, as defined in Twu et al. (2014), directly relates the different robot species with the CMY colors, i.e., if the color equipment of species ι is denoted as $p(\iota)$, then it can execute tasks t^j_β if $j \in p(\iota)$.

Having defined the task-space, (T, γ), and the task-map, ω, the distance between two agents i and j can be calculated as in Twu et al. (2014),

$$\delta(T, \gamma, \omega)(\iota, \kappa) = \frac{\sum_{t\in(\omega(\iota)\cup\omega(\kappa))\setminus(\omega(\iota)\cap\omega(\kappa))} \gamma(t)}{\sum_{u\in(\omega(\iota)\cup\omega(\kappa))} \gamma(u)}.$$

This task-dependent distance metric between different robot species can then be used to compute the *disparity* as shown in (11).

Having completely characterized the disparity, $Q(s)$, and the complexity, $E(s)$, of an experimental setup under a specific painting task, one can compute the heterogeneity measure associated with them according to (10). To this end, the third column in **Table 2** represents the heterogeneity measure of the different setups. The heterogeneity values have been computed for the sunset-painting task from **Table 1**, as well as for a generic painting task that considers the whole 8-bit RGB color spectrum as objective colors to be painted by the team. This latter task is introduced in this analysis with the purpose of serving as a baseline to evaluate the comprehensiveness of the proposed sunset painting task. As it can be observed in **Table 2**, the heterogeneity values obtained for the sunset and the 8-bit RGB tasks are quite similar and the relative ordering of the setups with respect to the heterogeneity measure is the same, thus suggesting that the sunset task used in this paper requires a diverse enough set of painting objectives for all the equipment setups proposed. Armed with this quantification of team heterogeneity, we now analyze how the spatial characteristics of the painting differ as the equipment configurations change.

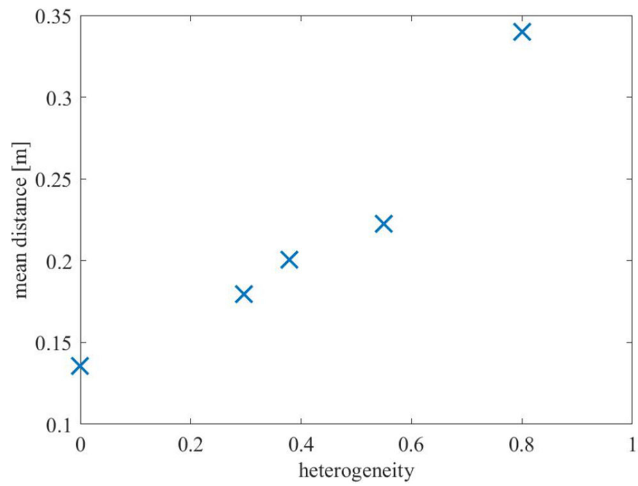

FIGURE 7 | Average distance from mean density input to the resulting center of mass over the input colors of the painting as a function of the heterogeneity among the robots [as defined in (10)]. As seen, with increasing sparsity of painting equipment on the robots (signified by increasing heterogeneity), the mean distance increases, indicating that colors get manifested farther away from where the user specifies them.

5.1. Color Distance

We first analyze the complex interplay between motion trails and equipment setups by computing the spatial distance between the mean location of the desired input density function specified by the user, and the resulting manifestation of the color in the painting. To this end, we use the *color distance* metric introduced in Androutsos et al. (1998) to characterize the distance from the color obtained in every pixel of the resulting painting to each of the input colors specified in **Table 1**.

Let $\rho(q)$ represent the 8-bit RGB vector value for a given pixel q in the painting. Then, the color distance between two pixels q_i and q_j is given as,

$$d_p(q_i, q_j) = 1 - \left[1 - \frac{2}{\pi}\cos^{-1}\left(\frac{\rho(q_i)\cdot\rho(q_j)}{\|\rho(q_i)\|\|\rho(q_j)\|}\right)\right] \left[1 - \frac{\|\rho(q_i) - \rho(q_j)\|}{\sqrt{3\cdot 255^2}}\right] \quad (12)$$

Using (12), we can compute the distance from the color of each pixel to each of the input colors specified by the user (given in this paper by **Table 1**). For a given pixel in the painting q and input color β, these distances can be interpreted as a color-distance density function over the domain, denoted as φ

$$\varphi(q, \beta) = \exp\left(-\frac{d_p(q, \beta)}{\varsigma^2}\right),$$

where, with an abuse of notation, $d_p(q, \beta)$ represents the color distance between the color β and the color at pixel q. For the experiments conducted in this paper, ς^2 was chosen to be 0.1.

Since we are interested in understanding the spatial characteristics of colors in the painting, we compute the center of mass of a particular color β in the painting,

$$C_\beta = \frac{\int_D q\varphi(q,\beta)\,dq}{\int_D \varphi(q,\beta)\,dq}. \tag{13}$$

The covariance ellipse for the color β at a pixel q is given as,

$$V_\beta(q) = \sqrt{(\varphi(q))}(q - C_\beta). \tag{14}$$

For each of the input colors, **Figure 6** illustrates the extent to which the color center of masses (computed by (13) and depicted by the square filled by the corresponding color) are different from the mean locations of the input density functions (depicted by the circle). For all the painting equipment setups in **Figure 6**, as the heterogeneity of the team increases, the mean of the input density function for each color and the resulting center of mass become progressively more distant. This phenomenon is illustrated in **Figure 7**, where the mean distance between the input density and the resulting color center of mass is plotted as a function of the heterogeneity of the equipment of the robots. For a given painting P, this distance is computed as,

$$d_c(P) = \frac{\sum_{\beta\in\mathcal{C}} \|\mu_\beta - C_\beta\|}{|\mathcal{C}|}, \tag{15}$$

where $\mathcal{C}$ represents the set of input colors, and μ_β represents the mean of the input density function for color β. As seen, with increasing heterogeneity, the mean distance increases because lesser painting capabilities on the robots do not allow them to exactly reproduce the input color distributions. However, even with highly heterogeneous setups, such as Setups 7 or 9, the multi-robot team is still able to preserve highly distinguishable color distributions throughout the canvas, which suggests that the coverage control paradigm for multi-robot painting is quite robust to highly heterogeneous robot teams and resource deprivation.

TABLE 3 | Color sectors throughout the painting used for the chromospectroscopy analysis, according to the density parameters specified in **Table 1**.

Sector ID	Objective color	x_{min}[m]	x_{max}[m]	y_{min}[m]	y_{max}[m]
1	Yellow	−1.2	1.2	0.6	1
2	Orange	−1.2	1.2	0.2	0.6
3	Pink	−1.2	1.2	0.2	0.2
4	Blue	−1.2	1.2	−0.6	−0.2
5	Cyan	−1.2	1.2	−1	−0.6
6	Yellow Sun	0.3	0.7	0.1	0.5

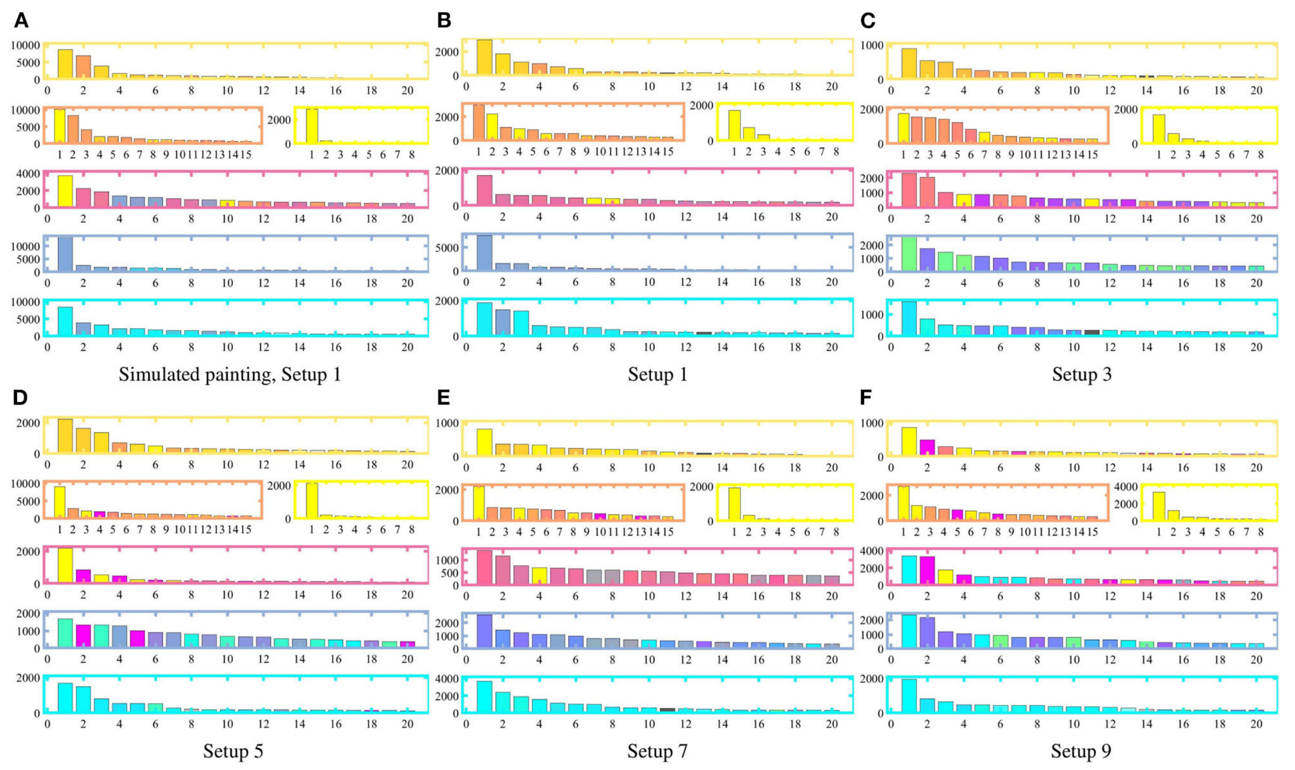

FIGURE 8 | Chromospectroscopy by sectors on the canvas (as indicated in **Table 3**) for each equipment configuration (as specified in **Table 2**). With increasing heterogeneity, and consequently, sparser painting capabilities of the robots, colors distinctly different from the target colors begin to appear in each sector. For teams with lower heterogeneity (Setups 1 and 3), anomalous colors in the chromospectroscopy typically appear from neighboring sectors only.

5.2. Chromospectroscopy

The second method we utilize to quantify the differences among the paintings as a function of the heterogeneity in the robot team is using *chromospectroscopy* (Kim et al., 2014), which analyzes the frequency of occurrence of a particular color over the canvas. To this end, the painting is divided according to the sectors described in **Table 3**, which are closely related to the areas of high incidence of the objective color densities in **Table 1**. A histogram representing the frequency of occurrence of each input color per sector is described in **Figure 8**. For the purposes of the chromospectroscopy analysis, the 8-bit RGB color map of the canvas is converted into a 5-bit RGB color map, by reducing the resolution of the color map and grouping very similar colors together, i.e., for an input color $\beta \in [0, 255]^3$, the modified color for the chromospectroscopy analysis in **Figure 8** is computed as $\bar{\beta} = \frac{\beta}{b}$, with $b = 2^3$.

As seen in **Figure 8**, the heterogeneity of the robot team significantly affects the resulting color distribution within each sector. More specifically, as the heterogeneity of the team increases, thus depriving the team of painting capabilities, the canvas presents more outlier colors which are present outside the corresponding target sectors. This is apparent in highly heterogeneous teams (Setup 9), where magenta-like colors appear in the top-most sector and cyan appears in the central sector. The three central sectors show a high occurrence of non-target colors. For slightly lesser heterogeneous teams, while the occurring colors often do not correspond with the target colors in the sectors—e.g., green in Sector 4 of Setup 3—, the colors seem

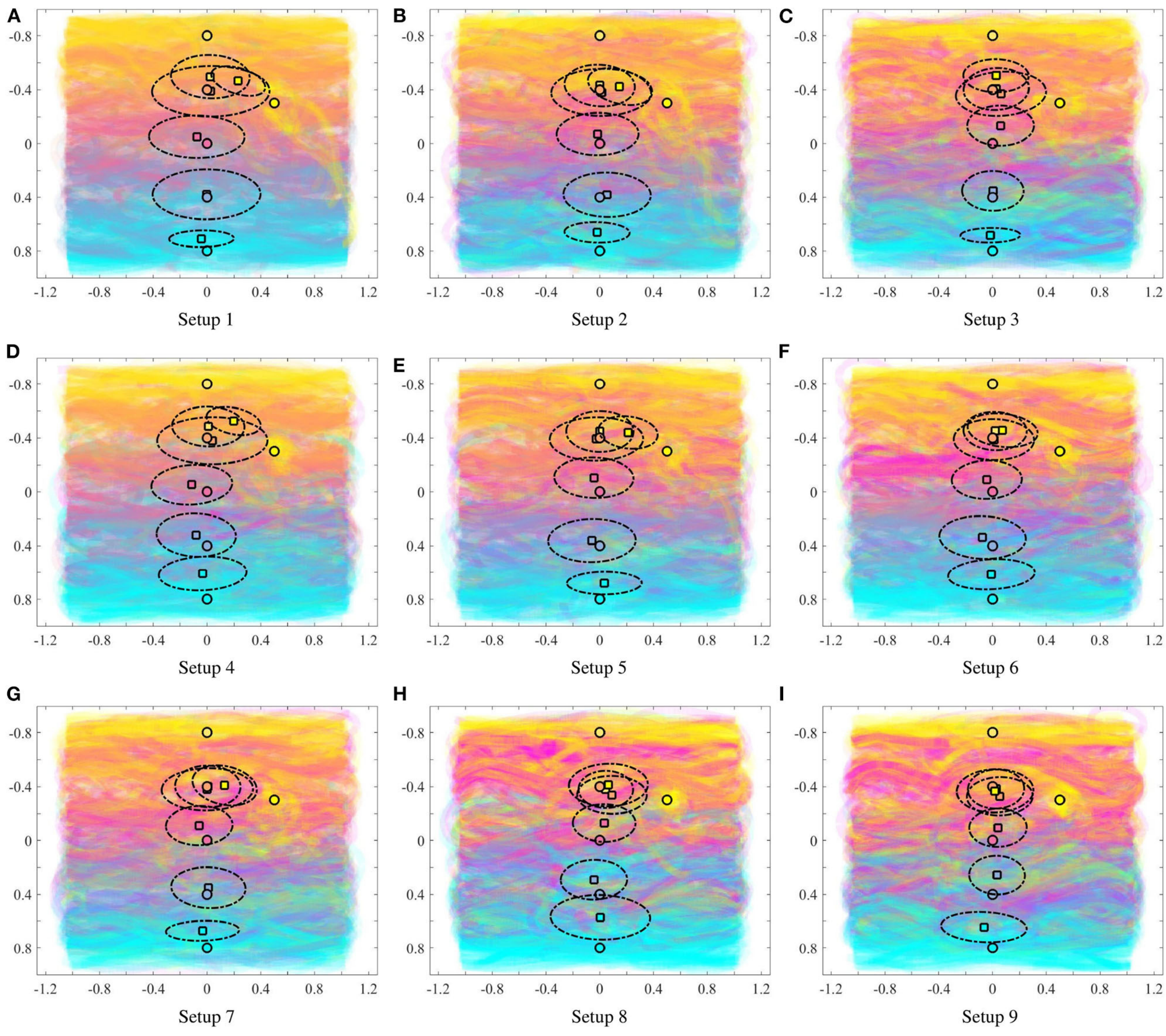

FIGURE 9 | Averaged paintings over 10 trials. Mean of the input densities (circle), center of mass of the resulting colors according to φ from (13) (square), and covariance ellipse (dotted lines). The heterogeneity in the painting equipment of the robots has a significant impact on the nature of the paintings.

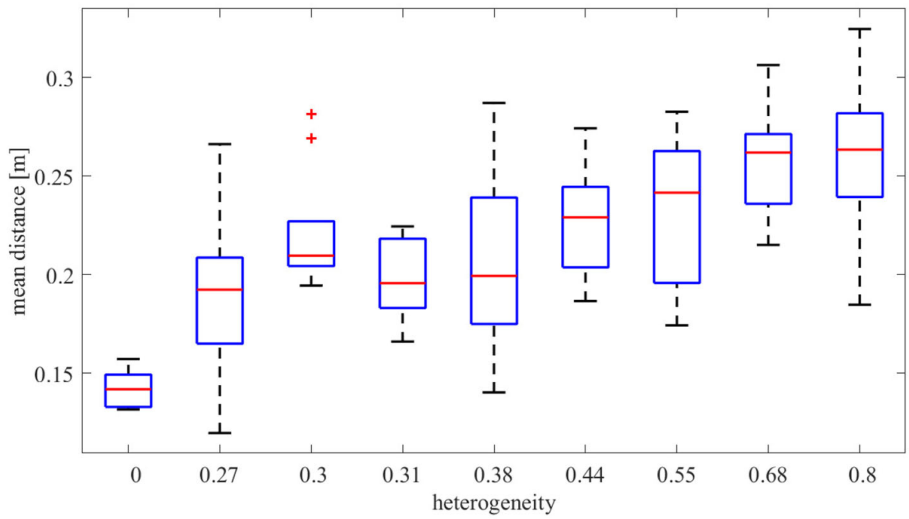

FIGURE 10 | Box plots of the average distance between mean density input to resulting center of mass as computed in (15) for the 9 different equipment configurations. The results are presented for 10 different experiments conducted for each equipment. As seen, the average distance increases with increasing heterogeneity among the robots' painting equipment.

consistent in their presence and correspond to limitations on the equipment of the robots: in Setup 3, all robots are equipped with only two colors, thus no robot is able to exactly replicate any target color with 3 CMY components by itself. In the case of teams with low heterogeneity, e.g., Setup 1 and Setup 3, resulting colors are mostly consistent with the input target colors. The presence of some colors which do not match the input corresponds to colors belonging to the neighboring sectors. Some specific examples of this include: (i) Setup 1: the presence of yellow in Sector 3, orange in Sector 2, and Blue in Sector 5, (ii) Setup 3: the presence of orange in Sector 1, and blue in Sector 5, (iii) Setup 5: magenta and cyan-like colors in Sector 4.

Indeed, as one could expect, the chromospectroscopy reveals that color distributions become less precise as the differences in the painting capabilities of the robots become more acute—observable as distinct paint streaks in **Figure 5** which stand out from the surrounding colors. Nevertheless, the distribution of colors on each sector still matches the color density inputs even for the case of highly heterogeneous teams, which suggests that the multi-robot painting paradigm presented in this paper is robust to limited painting capabilities on the multi-robot team due to restrictions on the available paints, payload limitations on the robotic platforms, or even the inherent resource depletion that may arise from the painting activity.

5.3. Statistical Results

In order to understand if the statistics reported above remain consistent for multiple paintings generated by the robotic painting system, we ran 10 different experiments with random initial conditions in terms of robot poses for each of the 9 equipment configurations described in **Table 2**. **Figure 9** shows the average of the paintings generated for each equipment, along with the color density averages, computed using (13). Although averaging the 10 rounds seems to dampen the presence of outliers, we can still observe how the distance between the objective color (represented by a circle) and the resulting color distribution (square) generally increases as the team becomes more heterogeneous. Furthermore, if we observe the color gradient along the vertical axis of the painting, the blending of the colors becomes more uneven as the heterogeneity of the team increases. This phenomenon becomes quite apparent if we compare the top row of **Figures 9A–C** to the bottom row **(G–I)**.

Quantitatively, this distancing between objective and obtained color density distribution is summarized in **Figure 10**, which shows the mean distance between the input density and the resulting colors. Analogously to the analysis in **Figure 7**, which contained data for one run in the Robotarium for five out of the nine setups, the average distances shown in **Figure 10** show that the resulting color distributions tend to deviate from the objective ones as the team becomes more heterogeneous.

The results observed in this statistical analysis, thus, support the observations carried out in the analysis of the paintings obtained in the Robotarium. Therefore, the characterization of the painting outcome with respect to the resources of the team seems consistent throughout different runs and independent of the initial spatial conditions of the team.

6. CONCLUSIONS

This paper presents a robotic swarm painting system based on mobile robots leaving trails of paint as they move where a human user can influence the outcome of the painting by specifying desired color densities over the canvas. The interaction between the human user and the painting is enabled by means of a heterogeneous coverage paradigm where the robots distribute themselves over the domain according to the desired color outcomes and their painting capabilities, which may be limited. A color mixing strategy is proposed to allow each robot to adapt the color of its trail according to the color objectives specified by the user, within the painting capabilities of each robot. The proposed multi-robot painting system is evaluated experimentally to assess how the proposed color mixing strategy and the color equipments of the robots affect the resulting painted canvas. A series of experiments are run for a set of objective density functions, where the painting capabilities of the team are varied with the objective of studying how varying the painting equipment among the robots in the team affects the painting outcome. Analysis of the resulting paintings suggests that, while higher heterogeneity results in bigger deviations with respect to the user-specified density functions—as compared to homogeneous, i.e., fully equipped, teams—the paintings produced by the control strategy in this paper still achieve a distribution of color over the canvas that closely resembles the input even when the team has limited resources.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

MS, GN, SM, and ME contributed to the conception and design of the study. MS, GN, and SM programmed the control of the robotic system and performed the design of experiments. MS conducted the data processing and the experiment analysis. MS, GN, and SM each wrote major sections of the manuscript. ME is the principal investigator associated with this project. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Machine Gaze: Self-Identification Through Play With a computer Vision-Based Projection and Robotics System

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Children begin to develop self-awareness when they associate images and abilities with themselves. Such "construction of self" continues throughout adult life as we constantly cycle through different forms of self-awareness, seeking, to redefine ourselves. Modern technologies like screens and artificial intelligence threaten to alter our development of self-awareness, because children and adults are exposed to machines, tele-presences, and displays that increasingly become part of human identity. We use avatars, invent digital lives, and augment ourselves with digital imprints that depart from reality, making the development of self-identification adjust to digital technologies that blur the boundary between us and our devices. To empower children and adults to see themselves and artificially intelligent machines as separately aware entities, we created the persona of a salvaged supermarket security camera refurbished and enhanced with the power of computer vision to detect human faces, and project them on a large-scale 3D face sculpture. The surveillance camera system moves its head to point to human faces at times, but at other times, humans have to get its attention by moving to its vicinity, creating a dynamic where audiences attempt to see their own faces on the sculpture by gazing into the machine's eye. We found that audiences began attaining an understanding of machines that interpret our faces as separate from our identities, with their own agendas and agencies that show by the way they serendipitously interact with us. The machine-projected images of us are their own interpretation rather than our own, distancing us from our digital analogs. In the accompanying workshop, participants learn about how computer vision works by putting on disguises in order to escape from an algorithm detecting them as the same person by analyzing their faces. Participants learn that their own agency affects how machines interpret them, gaining an appreciation for the way their own identities and machines' awareness of them can be separate entities that can be manipulated for play. Together the installation and workshop empower children and adults to think beyond identification with digital technology to recognize the machine's own interpretive abilities that lie separate from human being's own self-awareness.

Keywords: robotic art, human machine communication technology, projection mapping, computer vision, human robot interaction, child psychology, self-identify

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BACKGROUND

Development of Self-Awareness

The maxim of "Know thyself" has been touted since the time of Protagoras, as it indicates ultimate understanding of our own identity and action that allows us to more objectively evaluate our influence on the world. Recognition of self-awareness and self-identity fosters understanding of our relation to ourselves and our society as children and adults. Experiments show that the affirmation that comes with self-awareness leads to increased compassion for one's own actions as well as increased positive social helping behavior following surprising incidents like an accidentally collapsing shelf (Lindsay and Creswell, 2014). Self-awareness increases the attribution of causality for negative consequences to the self (Duval and Wicklund, 1973), serving to deter blaming others and deflecting criticism. Publically suggesting self-awareness using a webcam reduces the bystander effect of not helping someone in need when other people are present (van Bommel et al., 2012). Self-awareness induced by a mirror even reduces aggressive action, whereas audience presence does not (Scheier et al., 1974). Thus, self-awareness and identity go hand-in-hand with socially positive behaviors that promote integration in society.

The development of self-awareness and identity in children occurs in systematic stages that are often assayed using their response to seeing themselves in a mirror. Throughout the course of 5 years after birth, children go through eras of confusion, differentiation, identification, and meta-awareness in interactions with a mirror, characterized by what they do with their own bodies and objects placed in conjunction to them, such as post-its attached to their heads (Rochat, 2003). The last awareness stage involves how they present themselves publically, as if imagining how the mirror can be projected in the mind of others (Goffman, 1959). From 6 to 10 years old, children begin to consider alternatives to their own identities and at 10 years old, can even consider that their personalities remain the same when the name is taken away (Guardo and Bohan, 1971). This suggests at this age, children begin incorporating awareness of another viewpoint's perspective into their own self-awareness (Mitchell, 1993). This development is thought to occur in conjunction with biofeedback from parents, who present a reflective view for the children much like a mirror does in regulating their affective states (Gergely, 1996). Children begin to understand themselves by seeing the way others see them. In particular, the awareness of not being seen gives rise to an identification of the self as apart from the others' gaze.

Self-awareness adaptation doesn't end with childhood. Reflexivity in social interactions in considering one's own current and past selves allows emerging adults to construct their self-identity in the counseling setting (Guichard et al., 2012). Self-awareness is also crucial in leadership development (Hall, 2004) and promoting well-being in jobs such as mental health professionals (Richards et al., 2010). Public self-awareness of adults in a controlled interaction is found to predict variables like social anxiety, self-esteem, and perception of others (Ryan et al., 1991), indicating its importance in determining self-competence and social success. This self-identity in adults is bound up with bodily awareness. Those who lose bodily awareness due to trauma or injury are ameliorated using self-awareness-based touching and performance in psychological contexts (Fogel, 2009).

Technologies for Self-Awareness

Getting good at theater and dramaturgy involves comparing one's actions to the action's perception, as well as collaborating together with other performers. This has led to the use of ideas from theater in teaching strategies for self-development. Studies have used collaborative theatrical projects to empower youths in such areas as creating meaning about the self (Beare and Belliveau, 2007), learning to improvise in hypothetical situations (Lehtonen, 2012), and achieving positive mental health (Ennis and Tonkin, 2015). One approach uses puppetry to enact fear, anger, sadness, and other emotion-based stories as part of a "feelings curriculum" to teach emotional awareness and self-comprehension to children (Maurer, 1977; LC, 2019). These traditions leverage the way theater forces individuals to reflect back on themselves upon identifying with actors in a scene. One system engages youths to use Twitter posts to emotionally affect physical actions of a puppet theater installation using a robotic arm in a video, allowing them to reflect on their communication for development of self-awareness (Yamaguchi, 2018). Essentially theater serves as an immersive version of a mirror that allows young people to gaze at their own actions and consequences as compared to those of others, driving a deeper meaning of what constitutes self-identity in the context of self-presentation. In particular, youths learn that social interactions involve presenting themselves in different ways in different contexts, much as actors play their roles in dramaturgy (Goffman, 1959). The practice of this self-presentation is made possible by both understanding the consequences of our own actions, and observing how others see us through their own lenses.

Interactive technologies for development of self-awareness have focused on vulnerable populations who have difficulty adjusting to societal norms due to their deficits in self-awareness, such as those suffering from communication and social disorders like autism and ADHD (Boucenna et al., 2014). Therapeutic strategies have included using touched-based devices to engage youths to foster development (Kagohara et al., 2013), applying virtual environments (such as VR cafes and buses) to allow youths to apply their social awareness skills incrementally without fear (Mitchell et al., 2007), creating serious games that effectively teach facial recognition in social situations (Serret, 2012), and utilizing social media platforms to enhance self-esteem by the way of profile identification (Gonzales and Hancock, 2010). Digital technologies of human-computer communication have been found to higher levels of private self-awareness compared to face-to-face communication, which heightened public self-awareness (Matheson and Zanna, 1988).

Of the various forms of communication technology, one of the most promising is robotics, for it enables physical interaction in addition to virtual ones at a distance. Early studies focused on using robots to imitate child action, generating a sequence of motor actions that reproduces a detected human gesture (Berthouze et al., 1996). This work has modeled social interaction as observation followed by motor control, producing statistical models of motor representations that attempt to capture the human-robot interaction, exemplified by a study utilizing a game played by the robot Vince and its human interlocutor (Sadeghipour and Kopp, 2011). While simple actions can be approximated by robot movements, complex interactions that involve environmental constraints and rules require applying statistical learning theory to average over the different possibilities in complex spaces for all possible movements, even in tasks as seemingly simple as putting objects into a box (Hersch et al., 2008). Recent work has modeled interactive tasks like tossing and catching arbitrary objects using both physics and computer vision to adaptively learn and generalize complex tasks (Zeng et al., 2020). One important contribution of related work is showing that using a game involving imitation with each other, human and robot become involved in feedback loops of reciprocal imitation, relying on human recognition and awareness on one hand and robot pose detection on the other (Boucenna et al., 2012). This begs the question of whether using simpler technologies like face detection is sufficient to elicit rich interactions that rely on human understanding rather than on complexity on the robotics side.

The use of robotics to elicit behaviors in human participants relies more on a rich interaction environment as opposed to a sophisticated computer vision detection model, due to the way humans are innately drawn to interpret even simple machine gestures as representing affective gestures analogous to human emotional behaviors (Sirkin et al., 2015; Knight et al., 2017; LC, 2019). Robots in this regard have taken such simple forms such as bubble-blowing agents (Feil-Seifer and Matarić, 2009), geospatial robots (Nugent et al., 2010), and gaze-directing toys (e.g., My Keepon) (Kozima et al., 2007), all using simple interactions utilizing remote control of robot interactions to promote pro-social behavior. The effectiveness of the strategy comes not from the intricacy of the interaction, but rather the rich set of environmental cues and interpretations available to the child that makes the experience rewarding. One way to increase the interaction and immersion in the physical environment is by augmenting it with strategies like projection (Greene, 1986). Recent work has been able to projection map custom imagery onto complicated forms like faces (Bermano et al., 2017) and moving objects (Zhou et al., 2016), opening up possibilities for single-object projection experiences that respond to human interaction. It is possible to map robotic responses onto interactive objects much like an immersive form of computer based sculpture (Keskeys, 1994). The projection would then provide an interface to the robot via an external material, adding an additional layer of interaction capabilities as if the robot is controlling the external visual interaction based on audience feedback.

General Approach

Given the considerations above, we decided to use the robot's own interpretive ability—its gaze—to show young audiences the process of self-awareness, allowing them to understand themselves by seeing the way machine sees them. We used a simple face detection interaction with a moving robot to engage young audiences to become aware of the self through looking at themselves on a responsive projection mapped face sculpture, relying on the innate human ability to interpret the interaction environment in an affective manner.

This approach leverages: (1) the way children learn of self-awareness through the way others see them (Mitchell, 1993), (2) the physical proxemics and performance-like interactions that robotics creates to make this learning embodied in the real world, (3) the richness in self-gaze-directed interactivity provided by environmental augmentation through the mirror-like projected sculpture, and (4) the collaborative learning and play through workshops in multiple media and perspectives.

MATERIALS AND METHODS

The experience consisted of the following main components: (1) a motorized security-camera-like robot that moves either casually on its own or in response to audiences to keep its gaze on a face in the crowd, (2) a projection system that maps an audience member's own face onto a 3D face sculpture whenever the audience's face is detected by the robot, (3) a feedback screen that allows audiences to see what the machine is seeing, i.e., whether a face is detected, to interpret the machine's awareness of the audience, and (4) a workshop where audiences are asked to escape the machine's detection by putting on disguises, showing a comparison of being seen vs. not being seen by the machine, demonstrating a difference in awareness by other entities.

Exhibition

A set of four Appro and Panasonic CP414 security cameras (circa 1980) were cleaned, refurbished, and mounted on metal plates. Two of the cameras were further chosen for prototyping, with their internal fisheye cameras removed and replaced by webcams connected to an Intel NUC 7 (Windows 10) mini computer. The internal circuit was taken out, and the lens chassis was then reattached over the webcam. The body of the robot was constructed from a rotating base plate and an arm that tilts up and down at two different joints (Lewansoul kit), spray-painted silver upon completion. The three degrees of freedom (one in rotation, two in tilt) were controlled using three LDX-218 servo motors connected to a controller board, which was interfaced to an Arduino UNO board using custom routines. **Figure 1** shows the look of the camera and body, which were designed to appeal to young audiences, evoking playfulness and a perception of simplicity as opposed to traditional mechanized robots. The movements of the robot were similarly designed for serendipity, as sometimes the robot moved to fix its gaze on a face of the audience member, while other times it simply moved side to side and up and down on its own. The video stream taken by the webcam was processed in Processing 3.3 using OpenCV (Viola and Jones, 2001). During the face tracking phase, distance from the center of the view to the center of the detected face was calculated live, and whenever the x or y distance was non-zero, a signal was sent from Processing to Arduino to move the appropriate motors in that dimension to point the camera directly at the center of the audience's face. When multiple faces were detected, the robot would direct itself at each face in succession after a one-second pause in position. At other times, a set of three predetermined movement routines had the robot scanning around the exhibition hall. Occasionally, the robot would also move its head forward or backward toward imaginary objects. To appeal to younger audiences, we created a narrative for the robot as a supermarket surveillance camera fortified with computer vision and repurposed to play and teach children about machine gaze and self-recognition.

A set of prototypes for the 3D face sculpture were made using different media, in order to investigate how well projection mapping works given the current lighting situation at the museum. We tried clay, paper mache, PLA (3D print), a mushroom-based polymer, and foamular (CNC). **Figure 2** shows two attempts in sculpture construction. We decided ultimately to work with foam due to the ability to scale up in size, the lighter weight of the material, the ability to precisely craft the 3D look of the sculpture using CNC, and its ability to reflect the projection imagery properly upon being painted. A 3D face model was constructed in Cinema4D, and one half of the face was transformed using the poly effect to look pixelated with large polygons. Thus, the two sides of the face looked slightly different under projection of a face, with one side appearing more digitally manipulated than the other. The models were converted to stl format and printed on a 48 × 32 × 8 inch foam. The face was painted white to allow projection image to reflect, while the rest of the foam was painted black and mounted on a dark-colored podium (**Figure 3**). Canon LV8320 (3000 lumens) projectors were used to project face images from a $\sim 40^{\circ}$ angle above the setup (**Figure 4**). The image was projection mapped onto the face sculpture and controlled from the NUC 7 computer using the Kantan Mapper module from Touch Designer v099.

Completed views of the main interaction area are shown in **Figure 3**. The camera-mounted robot sat at the left of the projected sculpture. To its left was placed a live-view screen that showed the audience what the camera saw. When no faces were detected, the projection looped through a set of faces from the Chicago Face Database (chicagofaces.org) as a default visual response while the robot scanned the room. When a face was detected, Processing scaled the subject's face to the size of the projected image on the sculpture and used Spout to send the live video stream to Touch Designer to project onto the sculpture. The robot could follow the audience face by rotating or tilting during this interval so the image displayed was always dynamic. The size of the face projected on the sculpture was always the same regardless of the audience walking forward or away due to the scaling done in Processing. The image resolution is thus lower when the audience is farther away from the robot. When a face was found, a yellow square was also shown on the screen to the left superimposed on the camera's view. The complete system is diagrammed in **Figure 4**, and shown in audience view in **Figure 5**, both in prototype and final exhibition forms. Ambient lighting in the exhibition hall was turned down so that the projected image could be seen. Unfortunately this reduces the reliability of the computer vision. Thus, two lamps were mounted, one for illuminating the side of the robot, the other for lighting the audience's face for proficiency of computer vision through the robot's webcam camera. The lighting was calibrated at the beginning of each day of exhibition (from May to September of 2019) to ensure optimal audience experience each day.

Workshop

A workshop opened to participants of all ages was created and presented 5 times at New York Hall of Science (NYSCI) by members of the museum's Explainers Program. At least half of the participants at each workshop were under the age of 18. Each workshop had 7–9 laptops with the capacity for 10–15 participants. The workshop began by asking subjects to draw a face while focusing on features like eyes, nose, lips, and glasses, as an exercise. For the next 5 min, everyone showed their drawings to the crowd, and the workshop staff showed a computer-generated face from thisfacedoesnotexist.com, highlighting uniquely human features and discussing briefly how computers see human faces differently from us. We also outlined the main goal of the workshop to understand and play with the way machines see us. The next 5 min were spent getting a laptop setup and navigating a webpage that shows how poses can be detected by the computer vision on the webcam on the laptop. In this phase, participants could get out of their chair and move around to see how it affects the pose determination.

For the main part of the workshop (the remaining 25 min), we introduced how machines learn to recognize specific faces and how we can escape their detection, a fun activity for younger audiences. We showed audiences a custom script based on an existing p5 sketch we used to train a face classifier (https://editor.p5js.org/AndreasRef/sketches/BJkaHBMYm). First, the audience clicked a button repeatedly to take pictures of their faces with multiple samples. After training the program, we let the participants come in and out of the view of the webcam to verify that the machine learning algorithm has learned a representation of their faces. Workshop staff were available to fix any problems children had, but overall we were surprised by the amount of computer literacy displayed by the children.

Next we provided props like fake ears, hats, garments, mustaches, and jewelry to allow participants to dress up to escape the detection of the program despite being seen by the webcam (**Figure 6**). In this stage we showed how audiences can exist independently of the awareness of the machine. We let participants pick one outfit and train the program on the same person's face but as model for a different face. At this point, audiences could put on and take off their disguises and see the program recognizing different faces as different individuals (**Figure 7**). For example, one participant would train the program with his own face until it outputs "Danny" whenever his face is in front of the webcam. Then Danny would dress up as a football player and train the program to recognize the disguise as "Eli" (name of a well-known football player in New York). Then Danny would escape the program's detection of "Danny" by dressing up as Eli and vice versa. Throughout the process the workshop staff informed the participants on educational details about computer vision and machine learning. For example, we showed how taking many pictures (samples) were necessary for good recognition, the way different angles and conditions of a face for a given training made the algorithm more successful,

FIGURE 1 | Robot head and body. **(Left)** The camera (head) was an APPRO model with lens and circuit replaced by a PC-connected webcam, mounted on steel plates. **(Right)** The body consisted of a steel frame joined by servo motors exhibiting three degrees of freedom, two of tilt and one of rotation, allowing the camera to face any direction in space.

FIGURE 2 | Prototypes of the 3D face sculpture. **(Left)** A clay model with right side sculpted to be human face and left side a polygonal surface. The size required turned out to be prohibitively heavy. **(Right)** A reduced-size foamular model cut by CNC from an stl model and painted white to properly reflect projected image. The final exhibition model was approximately twice times the width and twice the height.

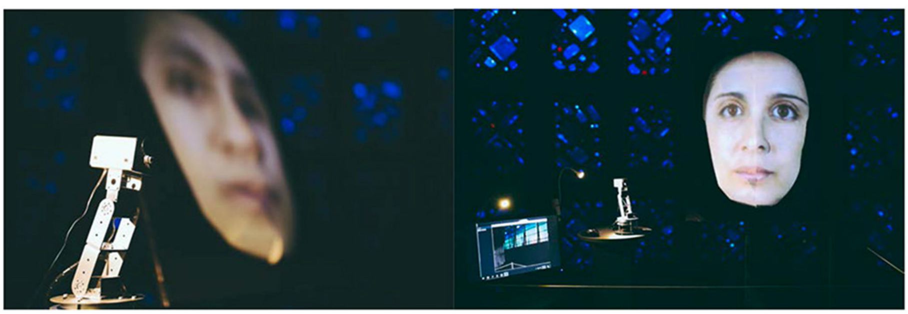

FIGURE 3 | The exhibition setup. **(Left)** The camera-mounted robot sat on a dark-colored podium to the left of the face sculpture with the image of a face projected on it from approximately a 40° angle. **(Right)** The setup as viewed from an approaching audience, with a screen on the left showing the camera view from the perspective of the robot, and giving feedback to participants for when their faces were detected. One lamp lit the robot while the other lamp provided ambient lighting on the audience's face. The projected video on the face sculpture cycled between faces from the Chicago Face Database when no audience faces were detected, and a scaled version of the audience's face when it is detected by the webcam on the robot.

and how these technologies were implemented in our own devices, etc.

After the workshop, we escorted the participants to the "Machine Gaze" exhibit (**Figure 8**), where they interacted with the robot and projected face sculpture freely for about 15 min before being given a questionnaire that asked the following 4 questions: "Where do you think the security camera comes from?," "What do you think the robot's purpose is?," "What do you think computer vision is?," "How do you think computers see us?." They were asked to answer in short phrases, which are coded qualitatively and presented (**Figure 9**). For a selected group of audiences, we followed the questionnaire with a qualitative interview to learn about their experiences in depth, asking them to elaborate on their reaction upon seeing their own image on

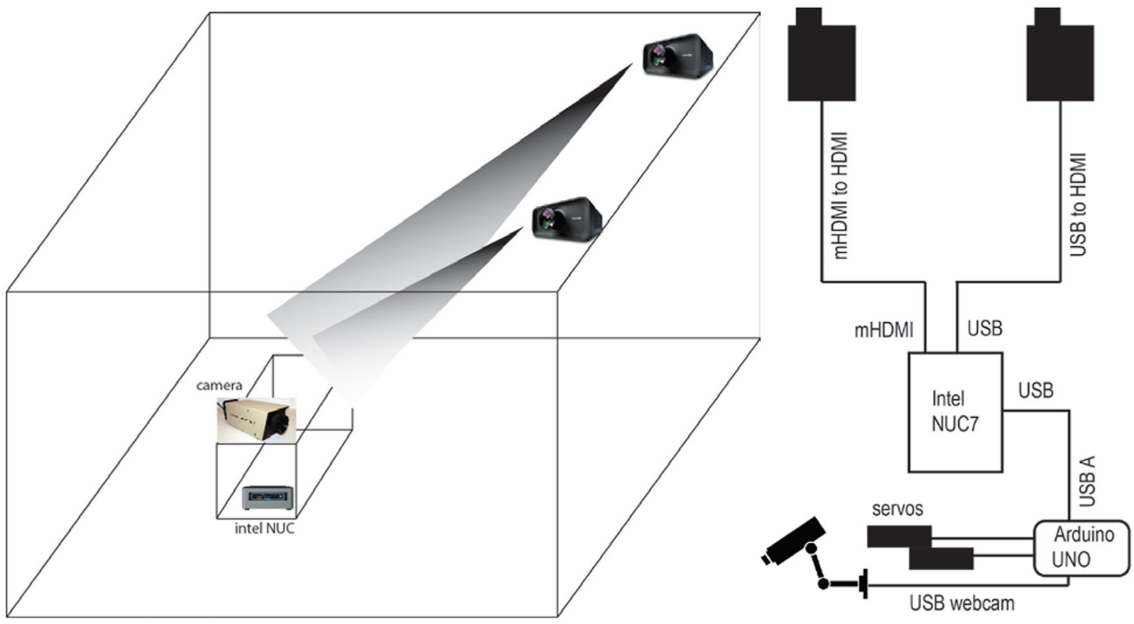

FIGURE 4 | Exhibition plan. **(Left)** Projectors on railings were used to illuminate the face sculpture in the setup, while the NUC computer and motor board components were hidden in the inside of the cabinet. **(Right)** The connection diagram shows the NUC PC as the controller that integrated webcam input to decide whether to project a database face or a real face, and to direct the servo motors via arduino UNO how to move to keep the audience's face in the center. In other situations, it directed the robot to pan and tilt in a preprogrammed manner.

FIGURE 5 | Audience interaction with the exhibit in prototype and finished form. **(Left)** Prototype stage interaction using a smaller face sculpture and brighter lamp to facilitate computer vision processes. **(Right)** A time during the final exhibition where the audience's face was detected, scaled, and projected onto the face sculpture. The projection mapping ensured the audience's face would be imaged on the face section of the sculpture. The audience's face, as seen from the robot's position, was shown on the screen to the left. At this stage, the robot followed the audience's face as it moved in space, as long as it was detected. When faces were no longer detected, the projection changed to flipping through the Chicago Face Database.

the sculpture, how they managed to catch up with the robot's gaze when it stopped following their faces, how they interpreted their own image on the sculpture vs. what the machine sees (as shown on the screen), how they reacted to the machine moving between multiple faces being detected, where they allocated their attention when the displayed face switched from their own to that of another and vice versa, etc. The questionnaire answers were qualitatively coded into categories, tabulated and plotted in R 3.6.0. Finally, we passively observed audiences as they interacted with the exhibit, taking note of their tendencies, moments of joy, moments of confusion, and issues that arose. The interview questionnaire, and observation data were used to further refine the exhibit after the workshop ended and the main exhibition timeline began at NYSCI.

RESULTS

Production and prototyping of the exhibition is seen here: https://youtu.be/V42towEXruk. Note the discretized movements of the robot tracking movement in 0:28. We decided to keep the discretized movements after audience members indicated in the first item in the questionnaire that it made them feel like the

FIGURE 6 | Workshop dress-up phase. **(Left)** Children selecting props, hats, decorations, and garments to wear that would allow them to escape the detection of a face classifier previously trained on their undecorated faces. **(Right)** A parent putting a fake mustache on her child after he put on football shoulder pads in an attempt to escape the computer vision's detection.

FIGURE 7 | Workshop face-detection phase. **(Left, Right)** Children wearing disguises observing whether the p5 face classifier script running on the computer was able to distinguish between their real faces and their new disguises. Participants were able to vary the amount of disguises and how they were put on until the classifier detected them as unique faces.

FIGURE 8 | Workshop exhibition phase. **(Left, Right)** Children were ushered to exhibition after the workshop and allowed to explore interactions with "Machine Gaze." They are currently looking into the robot's camera eye while also glancing to see if their face was detected by seeing whether their own faces appeared on the 3D face sculpture. Note that one child attempted to cover his face while looking through the slits between his fingers. The mustaches were left on by the children's choice.

camera was made long time ago in a "factory," and would be found in the "corners in rooms." The prototyping also showed that due to the OpenCV xml template used, even animal and cartoon faces were detectable (1:05), further allowing audiences to identify the machine's particular method of perception as something separate from human faculties. The initial face images we projected were also not uniform enough to suggest a set of possible machine perceptions, so we replaced them with the photos from the Chicago Face Database. Finally, we realized from preliminary interactions that the camera tended to move between multiple faces quickly in practice, so we set a delay of one second before it can move again during face tracking periods, so that audience members can see what's happening and react accordingly. Other materials/processes refined throughout the process included the material used to make the face sculpture, the lighting in the exhibition hall, the color of the podiums used,

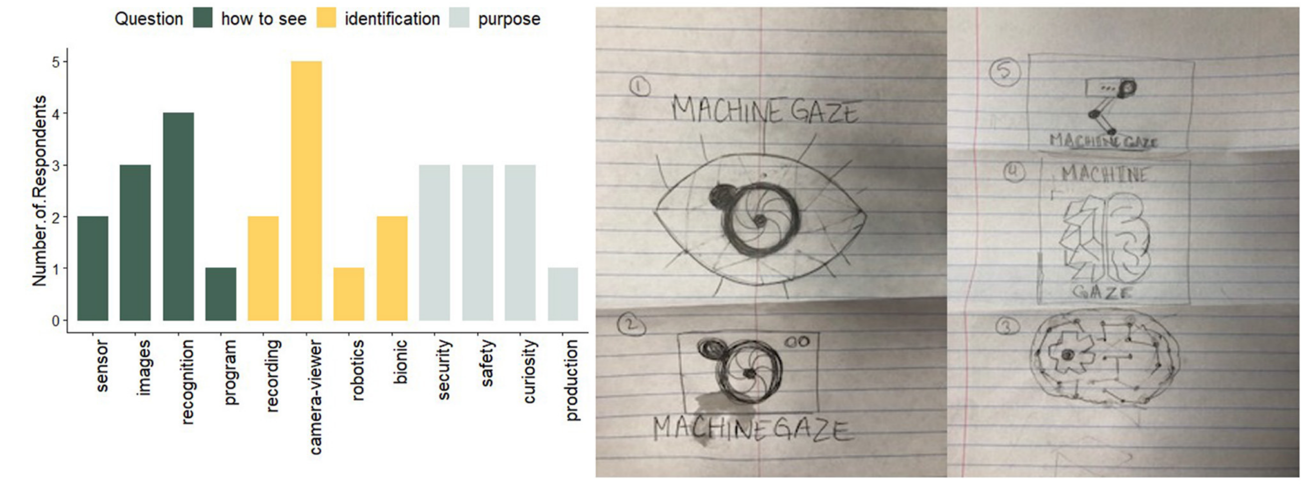

FIGURE 9 | Audience experience during the exhibition. **(Left)** Distribution of coded answers to each pertinent question in the survey given after exhibition experience ($n = 10$) (see **Appendices** for raw questionnaire and coding process). (Green) Answers to "How do you think computers see us?" ranged from mentioning the camera's sensor abilities, by taking images, by recognizing people, and by using a computer program. (Yellow) Answers to "What do you think computer vision is?" ranged from computer as a recording device, to machine vision as a camera that views its environment, to robotics, to computer vision as a bionic device. (Gray) Answers to "What do you think the robot's purpose is?" included a role to protect security, a way to promote safety, as a curious machine, and for production of resource. **(Right)** Drawing by a young audience member that served as her interpretation of what the "Machine Gaze" exhibit meant to her.

the speed of the robot movements, the number of projectors used, and size of the safety area around the robot, etc.

The full exhibition took place from May to September, 2019, with workshops kicking off the schedule in May. Documentation of audience interactions is here: https://youtu.be/kVoqkzZT4IQ. Our observation of the audience yielded three types of participants: (1) those curious about the device but refraining from making excessive contact with the machines (0:40), (2) those who take an active role to make expressive faces in engaging with the system (1:15), (3) those who bring others to the interaction by inviting them to the exhibit or enabling them to be in the view of the robot, creating a multi-face interaction (1:00). From our 5 days of observation, type (2) were the most numerous, with type (3) close behind, and perhaps exceeding type (2) on Sundays (the only weekend day we were observing). Interestingly, we found that group (1) audiences tended to come back to the exhibit at multiple points during their visits. One possible reason is that they interpreted the machine as standing guard over the exhibit, and hence came back to see if the machine would be off its guard (i.e., during periods where it stopped tracking faces). Group (2) audiences tended to make interesting discoveries in their interactions, such as using their hands to cover their faces so that the machine cannot see them (but they can see the machine move), and other pictures, people, and instruments in the environment as bait for the machine to focus its gaze on. Group (3) audiences included many parents who took their children in their arms while exploring the interaction together. They tended to initially guide the child's discovery, but frequently ended up competing with them for the machine's attention.

The audience survey given after workshop interactions showed different audience perceptions that we were initially unaware of **Figure 9**. While most participants equated computer vision with some sort of camera-seeing process (see yellow bars in **Figure 9**), some were associating it with recording or human-augmentation, topics with which computer vision is associated in popular culture. As in previous work, audiences tended to assign machine intelligence to the robot system beyond simple mechanical processes. In answer to how the robot sees, most participants attributed its ability to some recognition capability beyond simply sensor-reading or photography. We were also surprised to see that 3 of the 10 audience members surveyed also attributed the purpose of the machine to its curiosity or need for discovery, an inherently non-mechanical goal that assigns a human-like emotional content to the machine. People appear to be attributing advanced technologies to an old supermarket camera, assigning more intelligence to it than expected based on appearance, analogous to previous works in the area (Sirkin et al., 2015; LC, 2019).

However, due to the small number of participants ($n = 10$) and the free-form nature of the responses, we must warn against over-interpreting the data. Future work will be needed to tease out audience perceptions in complex mirror-like machine interactions, including with devices that perform only the mirror projection part, or only the machine looking-reflecting part. After the workshop, one artistic audience member drew some prospective logos for us. Her drawings equated the shutter of the camera to the human eye, and its hardware with the human brain, again assigning anthropomorphic qualities to the machine. We believe this reaction is due to the ability of the machine to move in space, indicate emotions like curiosity, aversion, boredom, intelligence, and attention through movement and changes in projected content. This may drive a sense of the audience feeling perceived by a being aware of the audience's persistence. It also hints at the use of robotics as a performance experience in evoking audience reaction.

Interactions from the workshop are shown here: https://youtu.be/pIRETXKZngg. Analysis was done on the videos after the workshop. For the face training phase, we saw that audiences liked to work as teams, usually with one member of the team (such as the parent) driving the interaction. Participants became creative with their interactions, such as turning around, glancing from beneath the table, and moving their face from side to side (0:48) as many ways to test the limits of escaping machine detection. We also observed parents teaching children about what it means to see their own image and how the machine interprets the face image (0:53). During the disguises section, we saw that the most popular items were hats (1:02). Frequently the participants helped each other put on the costumes and props and showed a feedback loop of asking for an opinion, then rearranging the props, and asking for opinion again, as if the questioner was using the opinion as a proxy for a mirror. Outlandish costumes were observed as well (1:11), because some faces did not easily escape the face detection algorithm, necessitating extreme measures. Interestingly, family members would sometimes wear matching outfits (1:18). This may be an indication of in-group affinity, but it could also indicate one member of the family teaching the other which disguises appear to be working. Generally the workshop was highly collaborative, with families working together and learning together. Finally, children tended to keep part of their disguises while visiting the exhibit (1:32). There was usually great excitement when seeing their own (disguised) faces appear on the 3D face sculpture, indicating their own shift in identity was registered by the perceiving system as well.

DISCUSSION

This intervention attempts to show audiences how perception of machines gazing at themselves can be a tool to engender self-awareness as a collaborative performance between human and machines. A first hint of these developments comes with the games that children invent while they interact with the robot. As detailed in Results, participants spontaneously perform games like covering their faces with their hands, making funny faces, seeing which of two faces the robot turns toward, etc. All these actions have a manifestation in the projected image on the 3D sculpture, some changing the detection of their face (covering with hands), some not changing the detection interaction (funny faces). The spontaneous development of these performative behaviors suggests an underlying learning process whereby children (and adults) acquire knowledge about whether they'll be perceived by the robot system based on the different performances they make. Their reaction to whether they are detected or not suggests an understanding of what the machine sees and how that relates to their concept of self. This understanding also seems to develop over the course of the interaction, with lack of understanding at first, followed by recognition of the machine gaze, then understanding of how they are perceived, and finally what they can perform to modulate this perception. To further test this idea, additional study is necessary to separate the self-identification process from the machine-perception process, and analyze how perception of each process emerges from interaction in the exhibit.

A second hint comes from the consistent attribution of human-like emotion, agenda, and behaviors to machines by audiences despite observing merely simple gestures, as previously studied (LC, 2019). The post-visit questionnaire results and exhibition audience observations both show some degree of assigning of human-like characteristics to the machine. For example, the machine is deemed to be curious by a large contingent of observers, and subsequent drawings of the machine endow it with human characteristics like eyesight. Audiences often treat the machine like a human-like creature both while it tracks their faces and when it ignores their faces. In the former they play movement games with it; in the latter they try to get its attention by moving toward the machine's eye voluntarily. This demonstrates that not only can machines track the human face, the human can track the machine face as well while trying to get its attention. This then creates a bi-directional interaction: if the audiences can see their own faces when the machine follows them, does the machine see its own face when they follow it? Further research beyond art interventions will be necessary to establish how these internal models about how each entity observes and is aware of itself may be able to provide educational moments for the participants themselves. Here, we propose through qualitative observation of audience interaction with an exhibition that such more complex dynamics involving processes of observing and modeling how machines see may be part of audience engagements.

A third hint comes from workshop interactions, where participants specifically escape detection of the machine's gaze by dressing up as another. The dressing-up serves as a narrative approach to differentiating who one is and is not (Bamberg, 2011), showing the actors who they are by letting them experiment with a situation where they are not perceived. This escape of detection may be critical in the audience members' self-concept, for they are able to recognize that sometimes they won't be perceived by others if they only performed a certain way. It's as if audience members are playing a game of public performance akin to self-presentation that hides their own true identities in the context of robots and environments that are not sophisticated enough to understand this form of deception. More interventions will be necessary to show how these mini-deceptions and playful performances affect what participants think of themselves in the context of environmental modulations.

CONCLUSIONS

Children's perception of being seen or not seen by external entities like mirrors and other people helps define their self-awareness. This identity is associated with their own self-presentation, which forms a performative behavior in public that in turn reinforces who they should be (Goffman, 1959). In this artistic intervention, we created a mirror-projection system that shows audiences their own faces, but only when interaction requirements are met, so that their perception of themselves are framed by what a machine sees, a form of performance in spatial interaction. We leveraged the prior demonstration of effectiveness in using robotics to help socialize children with communication disorders like autism (Boucenna et al., 2014) to create embodied physical actions that transform simply passive viewing to interactive behaviors that capture the subtleties of a self-perception-dependent form of performance. As audience interactions and experience shows, the exhibit and accompanying workshop leave participants more aware of how machine perception works, how their own actions interact with these perceptions, and how their own performance with the machines engenders cooperative awareness of the limitations of each.

The use of environmentally enriched robotic interactions is promising in artistic and social design realms, both for treating those with communication issues and for creating interactive experiences for the general public. This exhibition showed one possible intervention in provoking audiences to examine what their self is by using physical embodied interactions with a computer vision-enabled camera that detects their face. In the workshop, we showed that intervention contributes a sense of self identity for children, while in the exhibition, we argue that the distancing away from self-benefits audiences of all ages by allowing them to see themselves through eyes of the other. These technologies provide possible future scenarios of more intimate interactions that takes into account more affective types of human data beyond face detection. This work suggests a future direction toward smart environment and robotic interactions that can leverage human psychological insights to design interventions that aim to push for societal good.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was obtained from the participants or their legal guardian/next of kin. Written informed consent was obtained from the participants or their legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

RLC, AA, AB, and ST created the exhibition. RLC and ST produced the figures. AA, AB, and ST ran the workshops and collected the data. RLC wrote the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frobt.2020.580835/full#supplementary-material

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APPENDIX A

Audience Questionnaire given after the workshop.

Thank you today for participating in the Machine Gaze workshop at NYSCI. Please answer the following to the best of your abilities with a short answer (one phrase only).

1. Where do you think the security camera comes from?
2. How do you think computers see us?
3. What do you think computer vision is?
4. What do you think the robot's purpose is?

A BIG thank you from the explainers and staff of NYSCI. Hope you had fun, and keep playing with technology here at the museum today.

APPENDIX B

Examples of coding of responses to survey questions.

Question full		Raw responses								
How do you think computers see us?	Little thing in the camera	Camera	Black and white images	Code (zeroes and ones)	Recognize us as shapes and images	Recalling things	Camera takes a picture during video	Through the lens	By figuring out where we are	Tracks our faces
CODE	SENSOR	IMAGES	IMAGES	PROGRAM	RECOGNITION	RECOGNITION	IMAGES	SENSOR	RECOGNITION	RECOGNITION
What do you think computer vision is?	Looking through a vision	Camera	Microscope	Machine lens you see (you see through a machine lens)	You look at something too long that it starts to affect you.	Recording	Robots	Camera lens	Machine for eyes (machine or bionic eyes)	Video recorder
CODE	CAMERA-VIEWER	CAMERA-VIEWER	CAMERA-VIEWER	CAMERA-VIEWER	BIONIC	RECORDING	ROBOTICS	CAMERA-VIEWER	BIONIC	RECORDING
What do you think the robot's purpose is?	Looking from the corner	Making things in factory	Security, spy, prevent thief	Hidden security cameras	To see what happens around you	Camera makes sure nothing goes wrong	Makes sure people are safe	It's just looking around	Make sure everyone is ok	Monitor the crowd
CODE	CURIOSITY	PRODUCTION	SECURITY	SECURITY	CURIOSITY	SAFETY	SAFETY	CURIOSITY	SAFETY	SECURITY

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Lessons From Joint Improvisation Workshops for Musicians and Robotics Engineers

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We report on a series of workshops with musicians and robotics engineers aimed to study how human and machine improvisation can be explored through interdisciplinary design research. In the first workshop, we posed two leading questions to participants. First, what can AI and robotics learn by how improvisers think about time, space, actions, and decisions? Second, how can improvisation and musical instruments be enhanced by AI and robotics? The workshop included sessions led by the musicians, which provided an overview of the theory and practice of musical improvisation. In other sessions, AI and robotics researchers introduced AI principles to the musicians. Two smaller follow-up workshops comprised of only engineering and information science students provided an opportunity to elaborate on the principles covered in the first workshop. The workshops revealed parallels and discrepancies in the conceptualization of improvisation between musicians and engineers. These thematic differences could inform considerations for future designers of improvising robots.

Keywords: improvisation, robotics, artificial intelligence, thematic analysis, observational methods, workshops

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1 INTRODUCTION

This paper describes a series of workshops that were conducted with the goal of understanding what lessons researchers in AI and robotics can draw from the practice of musical improvisation in the process of designing improvising robots and AI-enabled musical instruments. We invited professionally practicing multidisciplinary musicians with substantial improvisation experience to attend a day-long workshop together with Mechanical Engineering (ME) and Computer and Information Science (CIS) graduate students. Themes extracted from the artists' experiences were later presented in follow-up workshops to additional CIS and ME researchers and discussed in the context of AI and robotics engineering. These investigations present a number of interrelated concepts of interest to designers aiming to build improvising machines. The investigations also revealed differences in how the conceptualization of improvising machines differs between practicing musicians and robotics engineers. These thematic gaps should be taken into account when these two populations collaborate creatively.

AI and robotics improvisation has been studied from the perspective of algorithmic structures as well as from that of cognitive models. In this work, we instead take an exploratory design-observation approach by asking professional improvising musicians and engineers to participate in a joint workshop. We started the exploration by posing a question to our workshop participants: "What is an improvising musical robot?" The motivation behind this question was to capture initial thoughts around combining AI with improvisation without encouraging bias toward any particular knowledge tradition. This opening question grounded the gathering as a joint venture between engineering and music by investigating cases for artificially intelligent improvisation agents.

During this initial workshop, four improvisation themes crystallized: Improvisation as *Spontaneity*, Improvisation as *Adaptability*, Improvisation as *Learning*, and Improvisation as having an *Inner Voice*. Improvisation as Spontaneity captures the requirement to embrace uncertainty and the element of surprise inherent in improvisation. Improvisation as Adaptability embodies the actions of an improviser when responding to environmental factors such as setting, audience, and ambience, as well as musical stimuli stemming from other members of the musical ensemble. Improvisation as Learning embodies the improviser's ability to use past knowledge to make on-demand decisions. Improvisation as an expression of Inner Voice focuses on the improviser's agency in producing personally distinctive content true to their conscience.

We also encouraged workshop participants to consider the role of AI and robotics in improvisation. This prompt uncovered three translative themes for AI and robotics: Improvisation as *Randomness*, Improvisation as *Assistance*, and Improvisation as *Data*. Improvisation as Randomness is the act of an artificially-intelligent agent causing disturbances during a musical performance. Improvisation as Assistance is about using AI and robotics to assist the decision-making process and provide feedback for human improvisers. Improvisation as Data highlights the fact that sound as data can be fed into a machine learning model. While these translative themes might suggest that many workshop participants see AI improvisers in a diminished role, workshop contributors also repeatedly considered AI and robotics as "superhuman," embodying the idea of artificially intelligent agents transcending the human physical body, memory, and capacity to improvise.

We conducted two follow-up brainstorming workshops with researchers to further explore how engineering and CIS researchers conceptualize notions of improvisation based on insights from the joint workshop. The goal was to develop, explore, and solidify the ideas that came up in the first workshop. As a result of all three meetings, we argue that the themes that emerged from the musicians' *human* experiences of improvising both contrast and match the way that the group conceptualized *machine* improvisation. Our findings point to considerations that may be useful to designers of improvising robots trying to bridge the engineering and musical improvisation communities.

2 THEORETICAL BACKGROUND

The themes explored in the workshops can be viewed against a background of literature from cognitive models of human improvisation in non-artistic realms on the one hand (as cognitive models often inspire AI and robotics computational models), and from theories and practices in artistic improvisation on the other hand.

2.1 Cognitive Models of Improvisation

Cognitive scientists have long identified the human ability to improvise as central to our problem-solving processes, and in particular the ability to create previously unknown solutions to existing problems. They see its importance particularly when it comes to real-time decision-making under time pressure (e.g., Moorman and Miner, 1998; Mendonca and Wallace, 2007).

2.1.1 Temporal Convergence During Environmental Turbulence

Mendonca and Wallace (2007) conceptualize improvisation as the temporal *convergence of planning and execution*. This definition of convergence is consistent with empirical accounts, from disaster response, through medical diagnosis and treatment, to sports. Analysis of these scenarios define improvisation as a situation in which thinking and acting, or reading and reacting, come together (e.g., Irby, 1992; Bjurwill, 1993). Moorman and Miner's analysis focuses on product development, and finds that improvisation occurs when an action is required, no plan is in place for the situation encountered. Improvisation events are most frequent when there is increased "environmental turbulence," a situation where information is flowing faster than it can be processed. In these cases, agents draw on short-term cues to make decisions, rather than integrate long-term prior information. These findings point to the fact that improvisation could be useful in areas of anticipated robot deployment, such as in medical or emergency response scenarios. Empirical evidence in both Mendonca and Wallace and Moorman and Miner shows that in those situations of turbulence, improvisation can result in better outcomes than planning. However, their detailed analysis also finds that long-term knowledge that existed prior to the improvised event positively affects improvisation outcomes. These findings suggest that a combination of learning, spontaneity, and adaptability are central to successful improvisation in dynamic settings.

2.1.2 Problem Solving, Planning, and Re-Planning

A different cognitive view of improvisation comes through the lens of problem-solving (Newell and Simon, 1972), where agents navigate from an existing state to a goal state. The above-stated situations of reacting to environmental turbulence can then be thought of as the addition and deletion of problem states, as well as the reclassification of the current state, or the redefinition of states as goal states. The planning problem of finding paths through the problem state is thus transformed into finding new paths through the problem state space (Ramalho et al., 1999). If this happens under time pressure, improvisation may be necessary. An additional cognitive problem facing an improvising agent is knowing *when* to diverge from an existing plan. This can be in response to time pressure or when it is unlikely that reasoning can result in an appropriate action (Mendonca and Wallace, 2007). Improvising agents also need to make comparisons between similar action and state paths in order to correctly categorize alternative paths of action (Horty and Pollack, 2001).

2.1.3 Slow Monitoring and Fast Reactive Control

From a computational modeling perspective, researchers have suggested that improvisation relies on a two-stage model of activity, including a slow process that monitors and evaluates the action of an agent and compares it to incoming feedback, and a faster one running as an open-loop motor program which cannot be interrupted (Glencross, 1977; Pressing, 1984). Training and learning in these frameworks are modeled as the progressive decrease of cognitive load by offloading motor programs to open-loop memory. Researchers have also offered models of opportunistic planning and of two-step decision-making systems in which the improviser first uses long-term memory to select a subset of appropriate actions and then uses rapid decision-making based on instantaneous feedback to select among those actions (Hayes-Roth et al., 1997; Rousseau and Hayes-Roth, 1998).

2.1.4 Declarative and Procedural Knowledge

Mendonca and Wallace (2007) offer a cognitive model which includes an ontology for declarative knowledge and a decision logic for procedural knowledge, both of which the agent possesses. Their framework includes processes that can compare planned routines and alternative action sequences and can produce mappings of interchangeable resources to be used in real-time for opportunistic action. Canonne and Garnier (2011) emphasize additional useful concepts in their cognitive model of improvisation. These include considering a gradient of time scales in decision-making, from fractions of seconds to several minutes. They tie this into a model of information processing which models the dynamics of an agent's objective and intentions. Finally, they account for cognitive load and boredom for when action replacements need to occur.

In summary, researchers in a variety of fields have proposed cognitive models for when and how people improvise. Some common themes are the operation on multiple time scales, the temporal convergence of learning and acting, and the ability to act based on new information. Different types of knowledge are acknowledged, indicating that improvisation is never a completely reactive skill, but that prior knowledge is also not enough to make decisions in the moment. These models provide a fertile ground for exploring the possibility of a computational cognitive framework for AI and robotics improvisation.

2.2 Theories, Methods, and Practices in Performance Art Improvisation

While most humans improvise in their daily lives, professional performers often study and practice improvisation in a structured way. Learning from their methods can help gain a better understanding of the systematic constructs of the improvisational process. This section provides a brief study of some of the theories, methods, and practices for improvisation documented by performing artists that could serve as a basis for a computational cognitive framework of artificial improvisation.

2.2.1 Referent Motifs and Variations on a Theme

A recurring concept in performance improvisation is the "referent" (Pressing, 1984; Magerko et al., 2009). In music, for example, this is often a melodic theme or motif. The improvisation's relationship to that referent can then take one of several forms: the ornamentation of the referent, a variation of the referent, or a temporal synchronization with the referent. Some authors emphasize that divergence from the referent opens the possibility for new structures (Klemp et al., 2008). The referent's origin can also be one of a number of sources. It can draw from a commonly accepted canon or from an instantaneously perceived event, such as an action done by another artist. In translation to human-robot interaction, this relationship could be modeled as 1) an action filling in an incomplete plan, or meshing the robot's action to the current human action sequence (ornamentation), 2) an alteration of an existing plan, either from an offline database or based on currently perceived human action sequences, or 3) time-warping an existing plan to match the action sequence of the human.

2.2.2 Object Memory and Process Memory

Looking at the training of improvisers, we often see the repeated performance of referents alongside variations on the referent. This practice enables the improviser to learn two distinct things: One is the "object memory" of the referent, building up a database of canonical knowledge. The other is "process memory," which teaches the agent schema of compositional problem-solving such as: variations, transitions, and so forth (Pressing, 1984). This division into two types of memory relates to the previously mentioned insight that improvisation occurs at two time scales. The referent evolves slowly, with little decision making, but with continuous feedback and monitoring. The short-term decision-making process works locally and on a shorter time-scale, using "process memory" such as variations in an open-loop fashion which enable it to act quickly. Acting on the slower time scales is thus often piece-specific, whereas acting on the faster time scales is training-specific. These concepts also map in ways useful to robot planning and control, and relate to the formalisms of "declarative knowledge" and "procedural knowledge" implemented in existing cognitive architectures (e.g., Anderson, 1996).

2.2.3 Mutual Responsiveness and Adaptation

An additional recurring theme is that of mutual responsiveness. Training manuals for actors and performing artists often emphasize improvisation games where actors need to react quickly to unexpected input from others. This is most strongly associated with Meisner's "repetition exercise" (Meisner and Longwell, 1987), which states that "acting [is] responding truthfully to the other person". Similarly, Maleczech speaks of *repercussion*: "The other actors are, for me, like the bumpers in a pinball machine. Often the next image will come directly from the response of the other actor" (in Sonenberg, 1996). Moore adds that "ensemble work means continuous inner and external reaction to each other" (Moore, 1968).

2.2.4 Embodied Improvisation

Finally, many texts on improvisation emphasize the embodied aspect of improvisation. Boal states that "the human being is a unity, an indivisible whole [. . .] one's physical and psychic apparatuses are completely inseparable [. . .] bodily movement 'is' a thought and a thought expresses itself in corporeal form." (Boal, 2002). Other texts also emphasize the physical aspect of improvisation (e.g., Moore, 1968; Cole and Chinoy, 1970; Broadhurst, 2004). Even texts that take a symbolic and algorithmic view of improvisation note that the embodied nature of the act is central (Johnson-Laird, 2002).

To summarize, an analysis of improvisation methods in the performing arts, theories, and practices can inform the proposed computational framework. Themes such as embodiment, mutual responsiveness, and chance relationships to a referent are examples of insights to be gained from exploring the performing arts and their practices.

2.3 Related Work: Computational Models and Systems of Improvisation

There have been many efforts over the past decades to translate improvisation principles to computational agents, both for the sake of staging human-machine improvisation systems and to understand improvisation practices in order to build non-performative AI systems. Two prominent, and well studied, examples are the *Voyager* system developed by George Lewis and the *OMax* system coming out of the Institute for Research and Coordination in Acoustics/Music (IRCAM).

2.3.1 Machine Improvisation as Inquiry

Voyager is an artificial improvisation system designed in the 1980s to engage with musicians on stage (Lewis, 2000). The system analyzes human performance and generates compositions in real-time. In Lewis's analysis of Voyager, he emphasizes its role as a non-hierarchical system that "does not function as an instrument to be controlled by a performer," but instead "emanates from both the computers and the humans." (Lewis, 2000). The flexibility made available by this type of composition and improvisation system challenges existing notions of composed vs. improvised music and, "deals with the nature of music." (Lewis, 2018) More recently, Lewis maps several reasons for the pursuit of machine improvisation, including the possibility to challenge traditional notions of interactivity, as well as larger societal questions of agency and choice (Lewis, 2018).

Similarly, *Odessa* is another example of a computational agent used to understand musical improvisation activities. Odessa is an artificially-intelligent agent used for cognitive modeling of human-interactive musical behavior (Linson et al., 2015). The model was used to evaluate a collaborative musical improviser through subsumption, a robotics architecture.

2.3.2 Statistical Learning at Two Scales

Developed in the mid-2000s, *OMax* is a real-time improvisation system that performs style-learning from human musicians in real time, and can respond via an improvisation-generation that includes metrical and harmoic alignment (Assayag et al., 2006). OMax is grounded in statistical sequence models, taking into account both short-term and long-term sequences, thus operating on two time scales. It also includes a multi-agent architecture, enabling it to instantiate different improvising agents into compositional topologies. The system is primarily focused on the analysis, learning, and construction of musical elements. In a recent dissertation, Nika elaborates on the OMax system, emphasizing the themes of *intentions*, *anticipations*, *playing*, and *practicing* (Nika, 2016).

2.3.3 Robot Improvisation as Embodied Opportunism

One of the authors of this paper developed a gesture-centric robot improvisation system (Hoffman and Weinberg, 2011). In contrast to previous works, the system was not structured around analysis and response, but instead used the robot's physicality and spatial movements to react in real time to musical impulses. This system highlighted several of the above themes, including operating on two time scales and on anticipation, but also it contributed the notion of *opportunism* to musical improvisation.

2.3.4 Themes for Machines Improvisers

In an effort to extract improvisation themes for computational agents, Magerko et al. (2009) videotaped professionals performing improvisation games and used a retrospective think-aloud protocol to extract themes. They found that improvisers use a number of cognitive processes, including inference from others' actions, narrative development, and referent use. However, they state that it "is not yet clear is how these different findings can be synthesized into a more singular, comprehensive viewpoint." The authors used insights from these workshops to build an improvising virtual reality agent (Hodhod et al., 2012). Their approach is grounded in logic and is embodied in a virtual character rather than an embodied robot.

Mogensen (2019) analyzes two Human-machine improvisation systems (Voyager, which is mentioned above, and *Favoleggiatori 2* Mogensen (2018)) from the perspective of Soft Systems. He describes such systems as a "nonverbal exchange between human and computer," using elements such as *memory*, *motivations*, *values*, and *search strategies*.

In a recent paper, Lösel (2018) surveys this work along with other research on artificial musical improvisation to suggest the following points of focus for computational models of improvisation: *embodiment*, or using the physical space and body of the agent for the improvisation process; and *chance and emergence*, suggesting that there should be a process in place which enables divergence from planning so that actions can be created. This work, however, has not been developed into a working computational system. Most recently, Kang et al. (2018) explored improvisation in the context of collaborative art practice and as a research lens for human-computer interaction, and also identified the following key themes: *reflexivity*, *transgression*, *tension*, *listening*, and *interdependence*.

In summary, researchers have long explored themes of improvisation in the context of machine improvisation, as well as in the context of computational models of human improvisation. Most of these works were developed with music in mind, and centered around disembodied musical agents, although some have also considered embodiment and robotics. The currently presented study does not propose to contribute to the rich theoretical literature in the field, but is instead aimed at exploring how the viewpoints of practicing musicians and robotics engineers engage with each other when they are placed in the context of a design activity to develop an improvising machine.

3 JOINT WORKSHOP

We began by conducting a full-day workshop that brought together two groups of experts related to the topic of robot improvisation. The first group were members of a professional musical ensemble with extensive improvisation experience on and off the stage. The second group were graduate and undergraduate students in Music, Mechanical Engineering (ME), Computing and Information science (CIS), and Design departments. The musicians were part of an ensemble that has previously collaborated with one of the authors (Papalexandri-Alexandri), and with one of the music students in the workshop. They helped invite students from a local music academy.

We also recruited a select group of ME and CIS graduate students in robotics labs across the authors' university to participate in a one-day workshop on AI, robotics, and improvisation. Students submitted a short, one-paragraph statement describing their relevant background experience and interest in the workshop. We received nine statements, five from graduate students in ME CIS, design, and four undergraduate students in music. Ultimately, seven of nine applicants participated in the joint workshop. Other guests included workshop organizers from the music department at our university and administrative staff from the local music academy.

Our motivation for inviting this group was to bring together diverse perspectives on improvisation and artificial intelligence to speculate potential futures for AI improvisation models. There were a total of sixteen collaborators in the workshop. The core of the workshop was structured around two roughly equal parts that addressed AI and robotics (part I) on the one hand, and musical expression (part II) on the other and was comprised of lectures, open discussions, technology demonstrations, and musical games.

The schedule was structured as follows, depicted in **Figure 1**: Session 1, a warm-up brainstorming activity, Session 2, an AI and robotics demonstration, a lecture and subsequent discussion, Session 3, musical improvisation performances and a subsequent discussion, Session 4, a written response extrapolation activity, Session 5, a musical game, and Session 6, a speculative design activity.

After introductions, the first activity was a warm-up exercise in which we asked workshop participants: "What is an improvising musical robot?" We wanted to capture initial thoughts on combining AI with musical improvisation before introducing insights or principles from both fields. We gave everyone 5 minutes to write down ideas that came to mind. At the end of the activity, we collected ideas ranging from an AI system capable of adjusting musical parameters based on real-time input to robots bringing a distinctive sound, voice, or resonance to a musical setting. These themes would be echoed later throughout the day's workshop.

The second activity included a robotics demonstration and a brief introductory lecture on AI and robotics (**Figures 2A,B**). The first part of the lecture gave a brief history of AI in the context of relating human intelligence to utility theory and logic. Next, a graduate ME student presented a demonstration in which an AI system was used to generate musical notes and gestures performed by Blossom, a social robot (Suguitan and Hoffman, 2019). The intention of the demonstration was to present AI and robotics to the musicians in the workshop in a tangible manner. The choice of demonstration was also intended to connect with a specific application of deep learning relevant to musicianship. As to be expected in the introduction of a new topic, much of the discussion was about the mechanics of the neural network underlying the demonstration. Musicians were curious, for example, about how an AI system compresses and decompresses music samples into and from a lower-dimensional space. There was also discussion about how musical applications of AI differ from other AI applications such as board games.

The third activity was a series of musical improvisation performances followed with a discussion debriefing the performances (**Figure 2C**). The session was structured around three musical improvisation duos. The first was a percussion duo using gongs. The musicians traded rhythmic and timbre phrases and used the gongs in a variety of physical configurations, such as hanging, lying on the table, and so on. The second performance was by a string duo that included a violin and an electric guitar. The guitarist made heavy use of electronic filtering and amplification devices, often using the noise generated by the devices as musical elements. The violinist also went beyond the classical use of the instrument, i.e., bowing and plucking, and improvising not only with the musical notes, but also with the physical use of their instrument. The third duo was of wind

PART I	PART II	PART III
Introduction	Session 3a: Musical improvisation performances	Session 5: Musical game
Session 1: Brainstorming - "What is an improvising musical robot?"	Session 3b: Musical Improvisation discussion	Session 6: Speculative design - Designing an improvising robot
Session 2a: Robotics demo	Session 4: Extrapolation - Leading research questions	
Session 2b: Introduction to AI		

FIGURE 1 | The first workshop was structured six sessions, divided into three parts. The first covered mostly robotics and AI, the second covered musical improvisation, and the third was more exploratory. Both Part I and Part II also had an exploratory element (Sessions 1 and 4).

FIGURE 2 | Four of the sessions conducted in the first workshop: **(A)** Robotics demonstration (Session 2a), **(B)** AI and robotics introduction and discussion (Session 2b) **(C)** Musical improvisation performance (Session 3a), and **(D)** Musical games (Session 5).

instruments, which included a flute and a trombone. Again, the flutist did not produce sounds in the classical way, but instead produced a variety of voiceless breathing sounds through the flute. The trombonist similarly used the instrument as both a brass instrument and as a percussion surface. Each performance lasted about 5–7 minutes. In each duo, one musician would emerge in the role of a leader with the other as their follower. The leader would set a tone, and the follower would either complement or contrast the sound. At times, the playing would converge before drifting apart again. In some cases, it seemed that the leader-follower roles were predefined or at least implicitly understood. In others, the roles seem to emerge organically from the improvisational interaction.

The subsequent discussion was seeded with the reflections of the musicians. The opening question was: "From a personal [experiential] perspective, what does it mean to improvise?" Responding to this question, musicians noted that improvisation is about being open to the environment around you, including other musicians. One musician described it like a conversation in which you need to communicate to your partner that you are open to what they have to "say." Musicians generally describe improvisation as a very specific type of intelligence (Matare, 2009). In contrast to scored music, one has to often choose between a huge number of possible actions in improvisation. Some musicians described it as the art of managing musical or logistical constraints and imposing or eliminating self-censorship while operating in a state of vulnerability. In line with this vulnerability, many also described improvisation as a risky activity. We will discuss many of these themes in the following sections.

In the fourth activity, all workshop participants individually responded to two leading research questions: "What can AI and robotics learn by how improvisers think about time, space, actions, and decisions?" and "How can improvisation and musical instruments be enhanced by AI and robotics?" Participants were given 10 minutes to respond to the two questions. They were first asked for written responses, and then one by one, each person shared aloud their responses to each question. Most commented on a robot's ability to go beyond the physical limitations of human capacity. An AI system can pursue multiple paths forward at any given moment, thus narrowing the space between intent and action. These themes are also discussed in detail below.

The fifth activity was a music improvisation game led by a graduate student in the field of music composition. Workshop participants used plastic cups to produce sounds and explore possibilities of *sound material* by transforming ordinary objects into instruments. Players were asked to improvise in several segments, inspired in turn by the concepts of "Being Human," "Being Machine," and "Being Intelligence" (**Figure 2D**). The improvisation was guided by a musical score, but players were encouraged to break from the score and interpret it as they saw fit. In *Being Human*, performers focused on creating music "with the consciousness of a human." In *Being Machine*, performers experimented with the sound and knowledge of the instrumental arrangement, driven by more mechanistic patterns and motivations. Finally, in *Being Intelligence*, performers created scenarios where they become machines with intelligence. Each rhythm produced by the players combined into a musical pattern, which was performed simultaneously by the full group of participants. This process led each person to make decisions about how to proceed playing based on the collective sound of the group. The experience created several forms of sound production and musical "algorithms" in terms of sound patterns and helped provide an embodied experience of both improvisation and algorithmic thinking.

The workshop ended with a speculative design activity for creating an improvising musical robot and a final show and tell. We split up into four groups and used this session as an opportunity to form multidisciplinary groups of musicians and engineers to produce ideas for an AI improvising agent. Workshop participants were encouraged to reflect on the day's activities and discussions and integrate them into a specific design. The outputs of the exercise were four designs that ranged from musical devices to an adversarial performance venue. The detailed descriptions of these designs are beyond the scope of this paper.

4 IMPROVISATION THEMES FROM THE JOINT WORKSHOP

During the joint workshop, several recurring themes emerged. To better reflect on the activities, we collected audio recordings of the above-listed sessions. In total, there were 113 minutes of recording from the one-day workshop split across five audio fragments. We then used a combination of automated transcriptions and audio review of these recordings to retrieve and collate these themes through affinity diagramming. We assigned tags at time points that corresponded to quotes from each of the themes. Themes were elucidated and refined through an iterative analysis process and consensus-building discussion among the authors.

By nature of their profession, the practicing musicians who participated in the workshop had a significantly longer life experience with improvisation than the other participants. As a result, the musicians contributed a larger body of data, and many of the discussion themes are grounded in their comments. Summarizing our insights from the audio transcriptions, we identify an overarching description of improvisation as the ability to generate new material in real time and of one's own accord while paying attention to or being influenced by one's surrounding environment. This ability, however, is not developed in the moment alone, but is based on *extensive prior practice* and knowledge of predominant motifs. The above definition contains four themes: Improvisation as *Spontaneity*, Improvisation as *Adaptability*, Improvisation as *Learning*, and Improvisation as an expression of an *Inner Voice*.

The majority of the data supporting each theme came from the 45-minutes improvisation discussion with the practicing musicians. For Improvisation as Learning, one quote came from the extrapolation activity. The themes mentioned above sufficiently capture the musical improvisation discussion's viewpoints, and none were broken into sub-themes.

4.1 Improvisation as Spontaneity

Improvisation as Spontaneity is the ability to generate *new and often surprising material in real time*. The real-time component of improvising steers improvisers to make choices about how to produce sound on the spot. As musicians, do not have an abundance of time to deliberate on what note to play next or anticipate how the overall tone of the performance will be when improvising, there is a degree of urgency more present in improvisation performances and less present in rehearsed performances.

When asked about the relationship between the past, present, and future in an improvisational setting, Workshop Participant 1 (WP1), a trombonist, stated that they wanted "to narrow that gap or eliminate it as much as possible so there is no future or past and that means bringing the awareness to the current sonic world." In closing this gap, one is fully cognizant of the immediate moment in time. This ties back to the view of improvisation as the temporal convergence of thinking and acting as stated by Moorman and Miner (1998). WP6 (pianist) describes anything improvised as having "a real-time component [where] actions are thought [of] and produced in the moment." It is at this critical moment where intention meets action.

Similarly, according to WP1 (trombonist), mastery of improvisation is "bring[ing] the intent up to the action," so that "there is no time delay" between thought and action; the strategy and implementation is almost instantaneous. This mode of being was described by WP5 (violist) as getting into "this space that feels like above your head," or being "in another zone" where "things are just happening." This points to a sublime experience associated with the spontaneous nature of improvisation.

Subsequent group discussions, however, introduced more subtlety to this theme. Spontaneity is not absolute, nor completely unrooted, but harkens back to existing knowledge, calling to mind the notions of procedural and declarative knowledge (Anderson, 1996). The musicians spoke about different levels of improvisation. WP6 (pianist) described it as follows: "There is one layer, free improvisation," where "everything is free," you play "with people you have never met." On the other hand, in many Jazz improvisation setups, musicians "practice ten thousand licks in all twelve keys, and then [they] go to a session and just play one of them." The degree of improvisation is determined by the number of free parameters available to manipulate while performing, but these are also a fluid aspect of the specific improvisation setting. This brings to the fore the complex relationship between spontaneity, pre-determined rules, and knowledge.

4.2 Improvisation as Adaptability

Improvisation as Adaptability is the ability to *pay attention and respond to one's surroundings* while producing material. It embodies the actions of an improviser when responding to environmental factors like setting, audience, or other members of the band and inherently requires giving up control. WP1 (trombonist) characterizes this process as being "subordinate to what the space needs sonically."

Improvisation implies an openness or willingness to be influenced by a surrounding environment. WP5 (violist), describes improvisation as "placing [your musical voice] in a state of openness or vulnerability so that external factors" influence "your voice and your experience." You are "allowing your voice to change in response." This can be being open to other musicians but also "playing solo, it could be [the] audience in the room affecting what you are doing." This point relates to mutual responsiveness in "repetition exercise" where actors truthfully respond to each other (Meisner and Longwell, 1987). However, "your perception of how the audience is feeling might affect what you [are] doing" (WP5, violist).

When improvising, the act of creation is intertwined within the context of the surrounding space. In this contextualization process, an improviser is continuously reading and interpreting the environment or the ambiance of the room to pick up on cues on when to shift gears, such as when to adjust tone, timbre, pitch, or sound. WP3 (guitarist) explains this process as follows: "I went into [the performance] with an idea [. . .] but my direction completely changed 5 seconds into it because [I was] making music or creating sound with another person." These signals may be as overt as an extended deep inhalation or as subtle as a nod from an improvising partner. Such signals are essential for collaborative interactions such as improvisational performances. Sometimes however, these signals are lost in translation. WP9 (percussionist) reflects on their duo performance with WP1 (percussionist) and on having missed their partner's intention: "If I had been able to realize the form [understand the structure of what the other person was playing], my ideas would have been completely different. [. . .] My ideas could have complemented that form."

4.3 Improvisation as Learning

Improvisation as Learning is the ability to generate material while not only paying attention to one's surrounding environment but also to build on the improviser's ability to use *prior knowledge acquired through study* or experience. The improviser must decide how to synthesize or incorporate discoveries into the creation of new sound material. Improvisation as Learning relates to three concepts: practice and feedback, exposure, and trust.

Building one's musical proficiency through practice and formal training can give an improviser a range of options to pull from when performing. In the training phase, improvisers frequently perform referents to learn object memory of the referent and process memory, which teaches compositional problem-solving (Pressing, 1984). WP6 (pianist) explains that "the more you know an instrument, the more options you have. [A] top-level percussionist [knows] a thousand ways to tap a surface," but a novice may only know a few ways to do so. "You can practice a specific way of playing a phrase or note" to develop proficiency. Still, the way "you contextualize" the learning "in the moment" is the determining factor of true skill as an improviser. On the other hand, not knowing an instrument proficiently could also be a blessing, as you have no preconceptions about how it should be played and or used. Too much knowledge can make the performer overly conscious about choices, causing them to rely more on their own and others' expectations. In this sense, a machine has an advantage by not having too much prior knowledge.

Mastery of any skill, including improvisation, requires a mechanism for feedback or an evaluation metric. The feedback loop enables an improviser to identify areas of improvement. An experienced improviser can balance mastery of the craft with the ability to contextualize the elements surrounding the performance.

Learning through exposure is discovering new ways of working or performing outside of one's traditional practices. WP10 (trumpeter) explains that "from a theoretical standpoint, you [do not] have to be a musician to improvise," but practically "people generally learn [the] basics and expand from there." In expanding a musical palette, WP2 (percussionist) says, "for me, as a musician, part of my training is I just listen to as much music as I can. I wish I had a better memory of these things [. . .] in the fabric of [my] musicianship."

Trust is essential in respecting other points of view or style of improvisation and having the willingness to adapt to disruptions or disturbances. It is also a process of transferring knowledge from one improviser to the next. In the workshop discussions, we learned that this knowledge of improvisation is tacit, and the sharing process is implicit and difficult to explicate. WP9 (percussionist) describes improvisation as a conversation between two people where there is "a certain continuity" or "mutual understanding that I am following. I am listening."

4.4 Improvisation as an Expression of an Inner Voice

Finally, the theme of Inner Voice relates to the ability to generate material *of one's own accord*. It stands in contrast to the previous themes, as it focuses on the improviser's agency in producing a distinctive sound, voice, or position. In that sense, it is rooted (and not necessarily spontaneous), it is one's own (and not necessarily responsive), and it is original (and not merely repeating prior knowledge). Inner Voice is about "bringing one's own distinctive sound, voice, and timbre to the musical setting" (WP5, violinist). This inner voice can be a product of past experiences leading to a unique characteristic or "essence" of an improviser. WP3 (percussionist) reflects after playing a duet performance: At first, "we [did not] agree on who would lead or follow [. . .] At that moment, I asserted a rhythmic form." In other cases, "there are a lot of recordings where [notable improvisers] do their own thing."

The first aspect of improvisation as having an Inner Voice focuses on how an improviser processes and synthesizes learning from experience. It involves intentionality in selecting which parts of past experiences to use, and others to disregard. This process is filtered through one's perception and interpretation of a given situation. This filtering process is one way to develop a style of improvisation. WP9 (percussionist) performed a duet with WP3 and recalled that "there were moments where one of us decided to do something different from the other to create [a] contrast that might open the options" for different sounds. This process follows the idea of divergence from the referent noted by

Pressing (1984) and Klemp et al. (2008), a mechanism to open up the possibilities for new forms to emerge.

In viewing consciousness as one's experience, consciousness becomes the peculiar characteristic of a person, making them produce a singular sound based on a unique inner voice. Improvisation as an expression of an Inner Voice might also be one's baggage or limited point of view (frame of reference). As WP3 (guitarist) describes it, "a lot of improvisation comes from your autopilot features" or "musical baggage," which consists of technical skills or experience. Personal bias left unchecked might prevent one from letting external factors influence their sound and comply with these influences, thus compromising the principle of Improvisation as Adaptability.

5 TRANSLATIVE IMPROVISATION THEMES FROM THE JOINT WORKSHOP

One of the defining features of the workshop was the convergence of thinkers from different fields. All workshop participants were encouraged to not only think about improvisation per se, but also the relationship between improvisation, robotics, and AI. We asked participants to also consider the role of an artificially intelligent machine or instrument in musical improvisation. As a result, during the extrapolation session, we uncovered "translations" of improvisation concepts into machine learning, engineering, and information science terms. We derive three translative themes which partially summarize 36 minutes of collective reflections from the extrapolation session.

5.1 Improvisation as Randomness

Instead of "spontaneity," when speaking of an improvising machine, the term "randomness" often came up in workshop discussions. Improvisation as Randomness was collectively thought of as the act of causing disturbances during a musical performance. It could manifest in the form of unexpected behavior from a robotic agent on stage due to the interaction between the robot's programmed task, physical form, and environment (Nehmzow, 2006). A robot can exhibit random behavior if any outside influence prevents it from completing a task, alters its physical structure, or changes its environment. For example, a robot could collide with the environment and break. Alternatively, sensor aliasing could result in "random" outcomes.

Randomness can also be used to take away control from a musician and to add risk. WP12 (design student) suggested that AI and robotics be used to "initialize or add more risk to the situation." It might "contribute a specific type of sound at the very beginning" of a performance to challenge performers to interact with a distinct sound. A musician could play a robot as an instrument, and it could resist in some way. In this scenario, the musician does not have complete control over the instrument. There could be "dynamic constraints in the instruments" that affect a musician's ability to play with another performer (WP13, CIS student).

A0lternatively, WP6 (pianist) suggests that AI and robotics "could learn a lot about human unpredictability or predictability, and we [improvisers] could enhance our improvisation practices [by collecting] data on how we form actions." A model might anticipate a person's next steps and create a diversion to reduce predictability by learning these patterns.

5.2 Improvisation as Assistance

Rather than thinking about a more egalitarian concept of "mutual responsiveness," the idea of an improvising machine "assisting" a human musician was prevalent. Improvisation as Assistance envisions using AI and robotics to assist the decision-making process and provide feedback for improvisers. Improvisation is a continuous activity of producing thoughts and actions. Conceptualizing the bridge between thought and action as decision points, this ongoing decision-making process can be mentally exhausting due to information overload. An AI system or a robot could assist in supporting these decision points.

For example, AI and robotics could help broaden the realm of possibilities for a human improviser. They could be used to expose a user to a diverse set of music samples to help widen their scope. The repository could act as a central hub for inspiration for those looking to build on their practice, where "one idea [could be] a seed for a lot of different ideas" (WP8, saxophonist). The model can then infer a musician's preference for a specific type of sound. Instead of suggesting similar-sounding output, the system might purposefully suggest different sounds to boost diversity and avoid over-specification (Kunaver and Požrl, 2017).

A converse way AI could assist in improvisation is through narrowing the scope of an improvisation opportunity, a critical component of the creative process. Given the spontaneous nature of improvisation, narrowing the scope of opportunity might be difficult and an improvisation space that is "too open" may make decision-making difficult. To quote one of our participants: sometimes, "musicians [. . .] think of multiple paths forward at any given moment, but can only choose one" (WP8, saxophonist). An AI system could steer this choice for the musician. Alternatively, a user can input all of these ideas into a system that synthesizes the data and identifies patterns that can help them move forward.

Finally, AI and robotics as evaluation models might be valuable to musical improvisers. We learned that musicians' overall consensus is they use their intuition when evaluating their performances. Evaluation models could provide a more objective feedback mechanism for improvisers, where performance metrics are supplied after each improvisation session. WP7 (Percussionist) imagined a network of sound models that could produce "a system of feedback in a digital audio workstation or the instrument" and work as an "unoriginality meter or appropriation meter." This could encourage musicians to explore new techniques and not get stuck on old habits. The tension between the musician's subjective sense of the improvisation's originality and the objective metrics might in itself support a performative quality.

5.3 Improvisation as Data

In contrast to "learning," workshop participants thought about "data" when considering improvising machines. Improvisation as Data highlights that sound is data and can be fed into a machine

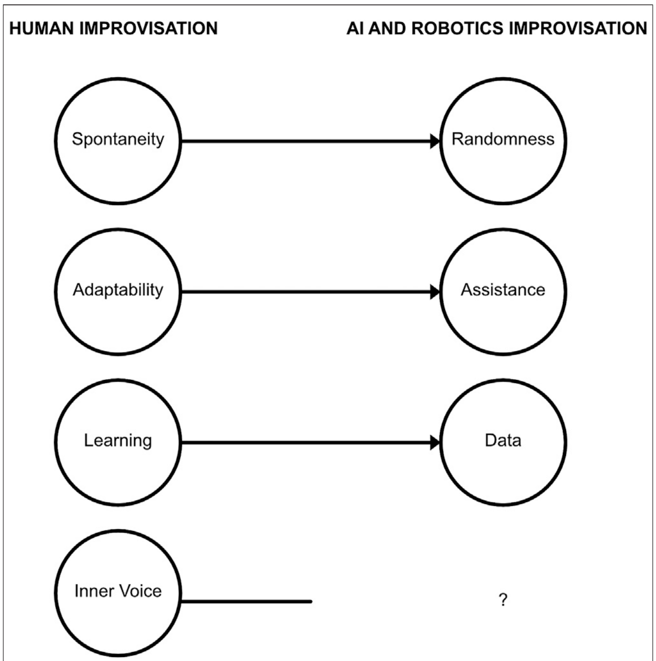

FIGURE 3 | Spontaneity, Adaptability, and Learning map onto the three translative improvisation themes for machines: Randomness, Assistance, and Data. The theme of Inner Voice is missing from machine improvisation.

learning model. WP7 (percussionist) imagines "all acoustic instruments [as] data collection and analysis tools." In this scenario, instruments are input devices equipped with sensors and become a "database library for the AI [model]" (WP14, music student). The initial sound data could be "enhanced to create a differentiation" of the original sound. WP15 (ME student) explains how a processing phase could be a model for learning different features. For example, "it could change the pitch of a piece or note density by looking at the structure of the data."

Once data is fed into a model, pattern extraction can occur. The model could then begin making inferences about specific music genres. Sound data with labels such as pitch, tone, and timbre can be used in supervised learning settings to make predictions. Recall that learning improvisation occurs both internally and externally. A single person's collective improvisation experiences are shaped by absorbing other examples of improvisation and practicing improvisation. These collective experiences can be inputs for a model that feeds "the machine of [memory] of other music and data" (P2, percussionist). The internal and external data can be parsed to help musicians make decisions as they improvise.

6 AI AND ROBOTICS AS "SUPERHUMANS"

A closer look at the translative themes (**Figure 3**) suggests that AI and robot improvisers would be diminished versions of human improvisers (randomness vs. spontaneity, assistance vs. adaptability, data vs. learning, no inner voice). Still, an opposing theme of superhuman technology also emerged repeatedly during the extrapolation activity. Workshop participants would describe AI and robotics in "superhuman" terms, illustrating the idea that artificially intelligent agents can be used to transcend human memory and capacity limitations. In this section, we describe several ways of limitation transcendence.

The first way of superhuman transcendence is related to surpassing human *physical* capabilities. Robots have been proposed to enhance human capabilities (Vatsal and Hoffman, 2018). WP3 (guitarist) comments that "robots can go beyond [the] physical limitations of what [humans] can do, in precision or stamina." For example, "it can control airflow much better than a human can." Another example is "the concept of deliberate practice [for] 10,000 hour, AI and robotics could do this much faster because they [do not] need to spend 10,000 hour [learning] how to play." Currently, "instruments are designed for ten fingers and within reach of a human arm span, but instruments no longer have to be designed with those constraints" (WP2, percussionist). Incorporating superhuman robots in improvisation could introduce new patterns of playing and new ways of improvising beyond human physical capability, as illustrated, for example, in Weinberg's work on super-human musical robots (Bretan et al., 2016; Weinberg et al., 2020).

AI and robotics could also overcome the cognitive load limitations that occur when improvising. WP13 (CIS student) liked "the idea of collapsing the space between intent and action" using the fact that computers are "super fast." WP3 (guitarist) noted that a model could "explore more of a nonhuman approach to learning improvisation, which leads to [. . .] concepts" that humans may not see as quickly or as obviously. Human memory has a limited capacity to store all improvisation genres, but this would not be a difficult task for an AI system. WP2 (percussionist) explains that "a computer [has] a really good memory bank [. . .]. We could feed [it] all music, all music from all parts of Africa, all time periods with whatever is documented."

Physical-cognitive crossover was also mentioned. WP4 (flutist) speculates a future feature where artificially intelligent improvisational agents "program things like different aesthetic brains so that we can have a corporeal experience of different sets of values." Agents would assist in "building empathy for other humans [. . .] opening up whole realms of performance practices of the past [and] perhaps the future from other places in the world." In this form of embodiment, agents provide human improvisers with an immersive bodily experience where embodied systems are connected to their environment beyond physical forces (Ziemke, 2001). In this space, "humans [interact] with robots [in] an artistic sense" or "robots [play] with [other] robots" (WP13, music student).

Not all participants agreed with the superhuman technology theme. Some pointed out limitations to what AI and robotics might contribute to improvisation. The act of improvisation is grounded in the human experience, which may not be replicated artificially. When asked the question, "What can AI and robotics learn by how improvisers think about time, space, actions, and decisions?" musicians noted the gaps to human-level improvisation that AI would need to overcome. One workshop participant stated that "we should teach [or] try to teach AI and robotics to be empathetic and to understand social cues." For example, "when to play and [when] not to play" or "when to begin or end a piece" (WP2, percussionist). WP4 (flutist) adds that "AI and robotics could learn different sets of cultural norms [..] and how to deviate from those norms." In this case, "improvisation for AI can be a good way of understanding human-centric concepts" (WP3, guitarist).

Some participants outright questioned the feasibility of teaching AI and robotics aspects of human improvisation. In response to the question of whether you could create improvising AI, WP2 (percussionist) protested that quite possibly "the answer could be, no." Moreover, the mastery of improvisation requires vulnerability. Improvisation as vulnerability is the ability to open oneself to risk. WP12 (design student) expressed that "there is a very important lesson that we can learn from our vulnerability, which is usually something that we do not see when we talk about machines and [AI]. We see them as really powerful tools." The hesitations described above indicate that the promise of an AI or robotic superhuman improviser comes with a caveat.

7 FOLLOW-UP WORKSHOPS

The knowledge of the musical performers dominated the discussion in the first workshop. To further understand how ME and CIS students conceptualize improvisation, we conducted two shorter follow-up workshops based on insights from the first workshop. We recruited a group of ME and CIS graduate students in robotics labs across the authors' university to participate in the follow-up workshops. Follow-up workshops were informal collaborative sessions that occurred at two robotics labs at our university across two campuses. The workshops occurred on separate dates, each lasting 2 hour. The first follow-up session consisted of two graduate students in ME and CIS departments. There were four workshop participants in the second follow-up workshop: two graduate students, one post-doctoral fellow, and one faculty member in CIS. None of the follow-up workshop participants attended the first joint workshop with the musicians. We recorded one of the sessions with a total of 101 minutes of audio captured in one fragment. In the transcription, we assigned tags at time points that corresponded to each theme. Whereas our initial workshop focused on learning about the musicians' improvisational experiences, the focus of the follow up sessions was to understand more deeply how improvisation applies to AI and robotics.

We began the follow-up by again asking the question: "What is an improvising musical robot?" We gave everyone 5 minutes to write down ideas. Ideas ranged from a "random music player," to a "robot that dances to music," to a "listening box" with big ears that helps a human improviser listen to music.

We then presented a preliminary version of the above-listed themes of improvisation (in **Sections 4** And **6**) and led additional discussion sessions. During the sessions, we uncovered more detailed nuances and hesitations about the "translations" of the concepts into machine learning and artificial intelligence terms beyond the findings from the first joint workshop. Improvisation as Assistance was further developed into three sub-themes: Improvisation as a *Design Process*, Improvisation as *Collective Intelligence*, and Improvisation as *Evaluation*.

7.1 Improvisation as Randomness

Randomness was again discussed as a promising way to incorporate AI and robotics in musical improvisation. Randomness specifically tied back to the loss of control that is inherent to improvisation. Building on the notion of "adaptability" as the ability to be influenced by one's surrounding environment while performing, a robotic system might act as an external force causing random disturbances during a performance.

Some suggested specific ideas of how a random AI system could be incorporated into improvisation. One route would be for it to "add machine noise" or "random sounds to a music piece" to make the music "sound like something else" (WP18, ME student). Building on this idea, WP17 (CIS student) imagined an improvising robot that takes "a song and inserts random pauses [or] notes." It could also do "unexpected things" outside of cultural norms, for example (WP17, CIS student). This random element in performance encourages a human improviser to rely less on previously learned material and generate solutions on the spot.

7.2 Improvisation as Assistance

In the follow-up workshops, much of the conversation revolved around the role of AI and robotics in assisting the decision-making process and providing feedback for a human improviser. This role was mainly conceptualized by framing the improvisation process around three process-oriented themes: design as a metaphor for improvisation, collective intelligence, and methods for evaluating improvisational elements.

7.2.1 Improvisation as a Design Process

In the second follow-up workshop, the double-diamond design process was used to model the divergent and convergent processes of generating new sound material (British Design Council, 2007). In the divergent phase, where ideas are generated, an AI system could take an initial idea or source of inspiration from a human improviser and create many configurations for an improvisational piece. On the convergent side of the process, where ideas are filtered into concrete concepts, an AI system can act as a filter, reviewing ideas from the previous state and giving recommendations for the next steps. The model could parse contextual data to help an improviser make decisions in the exact moment, monitor each musical improvisation session, and suggest areas of improvement, such as tone, pitch, and timbre. For this system to work, there must be a set standard for elimination or deciding where to go next. Some parameters might be the level of originality, fluency, pitch, or tone.

7.2.2 Improvisation as Collective Intelligence

A second way AI could assist a human improviser would be by viewing the collaboration between humans and technology as collective intelligence. WP20 (CIS student) describes a continuous transition between humans playing "music as we understand it" and "mostly noise" generated by algorithms. Here, humans would be at the beginning and end "nodes" of the diamond (mentioned earlier in the design process), and agents would be situated in the middle between the divergent and convergent sides of sound creation. The agents would draw "inspiration from any music that ever existed," and then a human improviser can select material to work into the piece. The agent could guide by "moving forward into a direction [that is] maybe not obvious to you," like a "blind spot detector" for music (WP20, CIS student). WP22 (CIS faculty) suggested the concept of an ecology of agents. Each agent has a different role in the sound creation process. One "agent that creates lots of ideas" and another that "picks some amplifies some." This ecology forms a collective intelligence that "takes away the pressure on any one of them to be perfect" (WP20, CIS student).

7.2.3 Improvisation as Evaluation

Improvisation as Evaluation is about using AI and robotics to provide a feedback mechanism for improvisation. A recurring theme from both follow-up workshops is the challenge of setting a standard for "good improvisation." We observed that it was challenging for most follow-up workshop participants to define a measure of accuracy, and specifically, deciding who or what gets to judge what is competent in improvisation. Nonetheless, an evaluation function might be based on "expert [or] audience" judgment, and some parameters could be "originality, completeness, fluency, [and] impact (reward)" (WP18, ME student). A potential model might read the audience or expert critic's facial expressions, gestures, output, and provide a score for improvisational performance. Evaluation can also come in the form of an AI instrument contributing to the music by generating sound output. Using an evaluation metric, explicitly set or learned implicitly, it could anticipate what the musical piece needs by "building and adding" to the music currently played and "chang[ing] and tweak[ing] things gracefully" (WP17, CIS student).

7.3 Improvisation as Data

ME and CIS students mostly viewed sound as input data into a machine-learning model. WP18 (ME student) noted that "music [is] data," so music files can be fed into a model that can "extract shared elements [or] patterns" thus, the music acts as "previously learned materials" in the system. In the transformation process, it can "edit some elements of the music" including the "beat, rhythm, [or] pause." The focus of these discussions was on the process of importing sound data into a model and extracting patterns. Unlike conversations from the previous joint workshop, there was no mention of using instruments as data collection devices.

7.4 Robots as "Superhumans"

Finally, it is worth noting that, in the follow-up workshops made up primarily of ME and CIS students, we discovered that the thought of robots transcending the limitations of human memory and physical capabilities was met with skepticism. This is a useful contrast to our findings from the joint workshop, driven by the musical performers. However, while the musicians highlighted the more nuanced human traits, such as vulnerability and life experience as obstacles for AI improvisers, engineering and CIS students focused on the limitations of technology.

For example, WP17 (CIS student) commented that robots are often unable to "do what humans do easily." WP17 (CIS student) focused on ways in which AI and robotics are still limited to physical constraints: "it [can not] defy gravity," or "it can not be in two places at once." Others chose to focus on the skills that robots can do well"storage, calculation, and computation. Instead of building a "superhuman," one might leverage the fact that AI and robotics can be used as a "memory" bank for human improvisers, and can aid in the "transformation and synthesis" of new sound creation (WP18, ME student).

8 DISCUSSION AND DESIGN CONSIDERATIONS

We discovered interesting connections between AI, robotics, and improvisation through bringing together musicians specializing in improvised performances with ME and CIS students in a series of design workshops. In our first workshop, four themes emerged as the musicians unpacked improvisation into its fundamental components. The first theme emphasized spontaneity, which is the ability to connect thinking and acting, compressing time, and making decisions on the spot. The second spoke of adaptability, responding to the environment, but even more so, to other improvisers. The third theme was learning, which builds on experience and knowledge, integrating the many years of skill-acquisition with the ability to act in the moment. Finally, musical improvisers emphasized the existence of an inner voice that guided their playing.

The workshop was framed to all participants to gain knowledge toward building improvising robots or AI-enabled musical instruments. In this context, the discussion did not remain in the musical realm alone, and all participants attempted to translate the complex structure of improvisation into engineering concepts. An analysis of the discussions surrounding building such systems reflected three of the above-mentioned four themes, albeit in diminished form. AI and robotic improvisers were imagined to use and provide *randomness*, would make use of *data*, and were suggested to *assist* the human improvisers. These three themes can be mapped to the notions of spontaneity, learning, and mutual adaptation (**Figure 3**). However, randomness must be viewed as a reduced form of spontaneity. Data and machine learning are an impoverished metaphors for human learning, especially for the cognitive-embodied kind required for an instrument. Similarly, assistance is a one-directional and subservient version of the rich back-and-forth that musicians provide in an improvised performance. The notion of an inner voice was completely missing from the discussion of AI and robot improvisers in all workshops.

What can designers of improvising robots and other AI-supported musical machines learn from the tension uncovered in our workshops? We present several considerations for design based on the themes and findings listed above.

8.1 Minding the Gap

When engineers think of improvisation, they run the risk of centering around technical concepts, such as randomness, data, and technology that assists a human musician. We recommend considering the gap between these notions and the richer ones brought forth by musicians: spontaneity, learning, and adaptability.

When a roboticist thinks of adding randomness to a machine improvisation process, they may instead consider to model spontaneity. Spontaneity affords one the ability to generate new and surprising ideas in real-time instead of limiting oneself to mathematical predeterminants or pseudo-random processes. Are random processes surprising at all? Do they capture the sense of "now" that spontaneity implies? Is randomness the contraction of the past, present, and future? We recommend designers of improvising robots to spend time sketching out a possible path from randomness to spontaneity when building improvising systems.

Similarly, robotic musical improvisation should be more than a functional output of sound data. The method of extracting patterns from data files is a flattened version of the learning processes underlying the ability to improvise. We encourage designers to explore the value to be gained from a more holistic approach to learning to produce sound and gestures. Our findings suggest an expanded notion of machine learning to include compositional, experiential, and contextual modes of learning.

Third, improvisation as assistive technology can fall short of the openness implied by the mutual adaptation in human improvisation. An improvising robot may be able to do more than assist a human in their exploration. We invite designers to ask: how can a robot contribute to sound creation while influencing and being influenced by its surrounding environment? Roboticists can use their designs to highlight this gap to consider power dynamics and calibrate user expectations around control and autonomy, much like previous interactive computer-based music models facilitated communication between performers, audience members, and instruments. For example, the works by George Lewis have established networks of non-hierarchical relationships between humans and nonhuman devices and between humans and humans to challenge institutional authorities (Lewis, 2017).

Finally, robot designers should ask: what is a robot's inner voice? Can one imagine the proverbial "baggage" that the robot brings to the performance? How does it interact with the other three themes, which were more natural for engineers to consider?

8.2 Superhuman, but Not Good Enough

Although robot improvisation was described in diminished terms compared to human improvisation, participants in the workshop often landed on the idea that AI and robotics could be superhuman, whether by overcoming the physical or the mental limitations of humans. The idea of robots overcoming human limitations is also a common theme in the robotics literature (Van Den Berg et al., 2010), while some have mounted a scholarly critique of robotics and AI as superhuman (Haslam et al., 2008). Why do participants view robotic improvisers as superhuman, given the above analysis that shows that the imagined roles for technology fall short of those identified for human improvisers? One may argue that the superhuman abilities that participants imagine are limited to rote physical and memory-related tasks. Be it as it may, we note the tension between the technological promise that machines may outdo humans in the task of improvisation and the lack of core competencies required of an improvising agent that machines can provide.

When questioning the possibility of a superhuman robotic improviser, musicians and roboticists listed very different rationalizations for their skepticism. Musicians and designers emphasized subtle aspects of humanness in improvisation, such as life experience, standards, vulnerability, empathy, and risk. Engineering and CIS students emphasized mostly technological limitations. The different rationales also highlight the diverging vocabulary of the two communities we worked with and emphasizes the need for a translative effort to collaborate between these two populations.

Future research in AI-mediated and robotic improvisation should make their artifact's relationship to the superhuman theme explicit. A robot may employ superhuman capabilities, such as computational power, to surpass human memory and physical capabilities when improvising. But roboticists must embrace and highlight the ways in which a robotic improviser falls short in their design. The tension between utopia and disappointment will enrich the expressive potential of a human-robot joint improvisation.

8.3 Fragility and Uncertainty as Metrics for Success

We also argue for a new paradigm in building AI and robotic models by embedding improvisation principles in the conception phase, as well as in the metrics for their evaluation. AI and robotics engineers usually measure their work with respect to metrics of stability, reliability, and performance (in the engineering sense). One of the gaps exposed in our analysis of the superhuman theme is that empathy, vulnerability, and risk are at the core of good improvisation.

Designers of improvising robots should imagine artificial improvising models that embrace uncertainty and fragility. In this alternative scenario, models are built under ambiguous and incomplete conditions that produce fluid and temporal systems. Models evolve into new creations where new knowledge is produced in real-time. Here, code might break, or robots might consist of collapsible or decaying components. A musician might have to build an instrument as they play on a stage. Also, roboticists must learn to be comfortable relinquishing some control since their creation might be used in a different manner than intended.

In summary, the convergence of experts from divergent fields could help roboticists and musicians who want to collaborate on building improvising machines make sense of both the promises and the gaps toward this goal. The qualitative exploration provided here could help guide toward productive themes to explore and warn of potential pitfalls in the translation of concepts between the performance and engineering communities. When examining all of the gaps mentioned above, it is also important that both communities should make explicit their delimited views of improvisation.

9 LIMITATIONS

The themes and insights provided above are subject to several methodological limitations. First, the workshops were not made up of a representative sample of musicians or researchers, but each was an organized research activity between existing collaborators. Along the same lines, the authors of this paper served in multiple roles: we were organizers of the workshops and active participants in the discussions. As a result, this paper's thematic analysis was not done blindly or by multiple, independent, and correlated coders. Instead, the analysis came out of a discussion of the insights gleaned from the documentation collected during the workshops. Subsequently, the work described here falls under the category of qualitative conclusions drawn from an embedded research activity, rather than a controlled study of music improvisation.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

All authors contributed to the development of the joint workshop; AC and GH contributed to the analysis of the data and to the writing of the article.

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Art, Design and Communication Theory in Creating the Communicative Social Robot 'Haru'

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Haru is a social, affective robot designed to support a wide range of research into human–robot communication. This article analyses the design process for Haru beta, identifying how both visual and performing arts were an essential part of that process, contributing to ideas of Haru's communication as a science and as an art. Initially, the article examines how a modified form of Design Thinking shaped the work of the interdisciplinary development team—including animators, performers and sketch artists working alongside roboticists—to frame Haru's interaction style in line with sociopsychological and cybernetic–semiotic communication theory. From these perspectives on communication, the focus is on creating a robot that is persuasive and able to transmit precise information clearly. The article moves on to highlight two alternative perspectives on communication, based on phenomenological and sociocultural theories, from which such a robot can be further developed as a more flexible and dynamic communicative agent. The various theoretical perspectives introduced are brought together by considering communication across three elements: encounter, story and dance. Finally, the article explores the potential of Haru as a research platform for human–robot communication across various scenarios designed to investigate how to support long-term interactions between humans and robots in different contexts. In particular, it gives an overview of plans for humanities-based, qualitative research with Haru.

Keywords: human–robot interaction, human–robot communication, art, design, design thinking, communication theory, human-machine communication

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INTRODUCTION

"Haru" is an experimental robotic platform developed to support research into human–robot communication from a number of disciplinary and methodological perspectives. The design for Haru's first prototype, Haru Beta (**Figure 1**), concentrated on developing the robot's physical form to include enough motion capability and other nonverbal affordances to support its emotional expression and communication in interactions with people (Gomez et al., 2018). The continued development of Haru will increase the robot's capacity to communicate in a number of other ways that complement its nonverbal expressiveness, including using a voice and potentially via other novel affordances, such as content projected onto nearby surfaces. Haru is thus being developed with a broad idea of communication in mind, encompassing language, paralanguage and kinesics (Sandry, 2015). Haru's flexible communication style is expected to support research into long-term

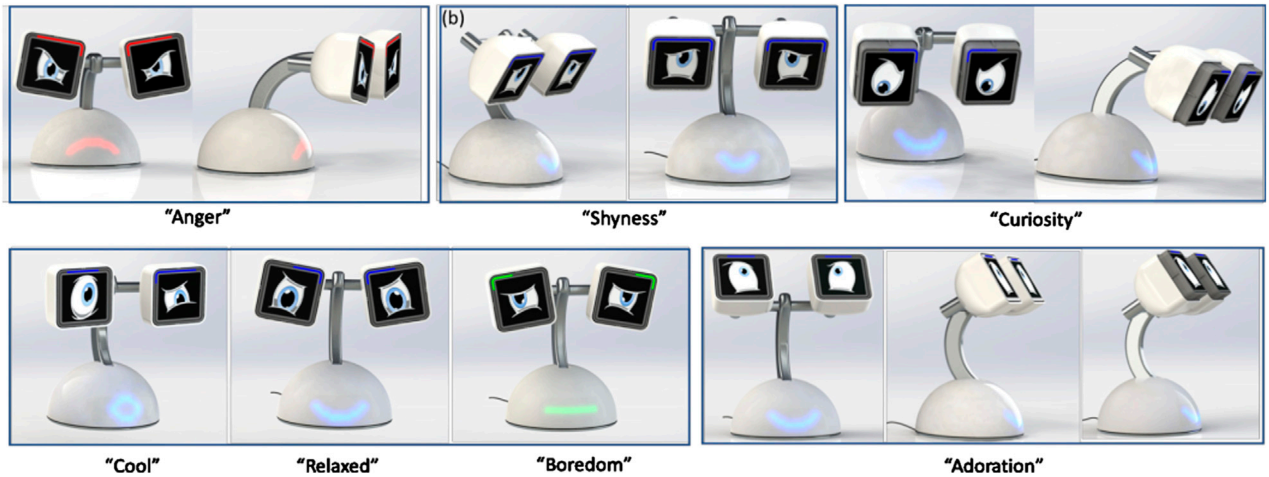

FIGURE 1 | Haru beta showing some of its emotive affordances.

human–robot interactions, since this robot's multimodal communication has the potential to draw people into communication and sustain their interest over time. This article focuses on analyzing and theorizing Haru's communication with people. Across different experimental contexts, Haru will likely be developed to use voice, facial and gesture recognition, allowing people to communicate with this robot using speech, facial expressions and bodily gestures.

The article begins by analyzing the design process for Haru Beta. It highlights how the work of visual and performing artists was integral in the development of this robot, while also examining how this shaped Haru's non-verbal communication style in relation to sociopsychological and cybernetic-semiotic theory. It then moves on to consider sociocultural and phenomenological theory, which offer alternative perspectives from which this robot's communication can not only be understood, but also developed further. The article therefore draws on a number of communication-theoretical traditions to examine Haru's ability to interact with people, combining analyses of communication as a science and as an art. To organize this wide-ranging theoretical and analytical trajectory, the article frames its discussion of human–robot communication across three elements: first, people's initial *encounter* with the robot, and how the robot might be recognized as a communicative other in this and subsequent meetings; second, ideas of *story*, drawing together the narratives that emerge not only as people interact with Haru, but also those told before, to frame the interactions, and after, to explain them; and third, *dance*, attending to the embodied nature of communication with Haru with the potential to support dynamic, overlapping verbal and nonverbal interchanges through which meaning emerges in interaction.

Having considered Haru's communication in this way, the article introduces various communication scenarios that will shape future experiments, analyzing interactions between people and Haru in particular contexts. Experiments with Haru will use qualitative methods to complement and extend quantitative approaches more commonly used in human–robot interaction research. Alongside this, the article emphasizes how looking at the whole process of multimodal communication with Haru, across the elements of encounter, story and dance, sheds light on ways to create robots that not only attract people's attention in the short term, but also are able to sustain meaningful communication in the long term, without becoming either irritating or boring.

ANALYZING THE DESIGN PROCESS FOR HARU BETA

The design and development of Haru Beta used a customized Design Thinking model to outline a process able to accommodate an interdisciplinary team of animators, performers and sketch artists working alongside roboticists. Commonly, Design Thinking processes begin with an Empathize stage, during which designers take time to empathize and potentially also engage with prospective users of the product being designed, before moving into a Define stage that identifies a clear statement of the problem the design needs to address (Damand and Siang, 2019). In the case of Haru, a robot destined to be a platform for human–robot communication research flexible enough to work across a number of scenarios, disciplinary perspectives and methodologies, these two stages were swapped (**Figure 2**). This allowed the team to take the initial step of defining their own overarching problem driving this robot's design; the need to build a distinctive, expressive and communicative robot that would support a high level of anthropomorphism without raising people's expectations too high (Gomez et al., 2018).

Even in its modified form, as for the Design Thinking model more commonly used, the process for Haru's development

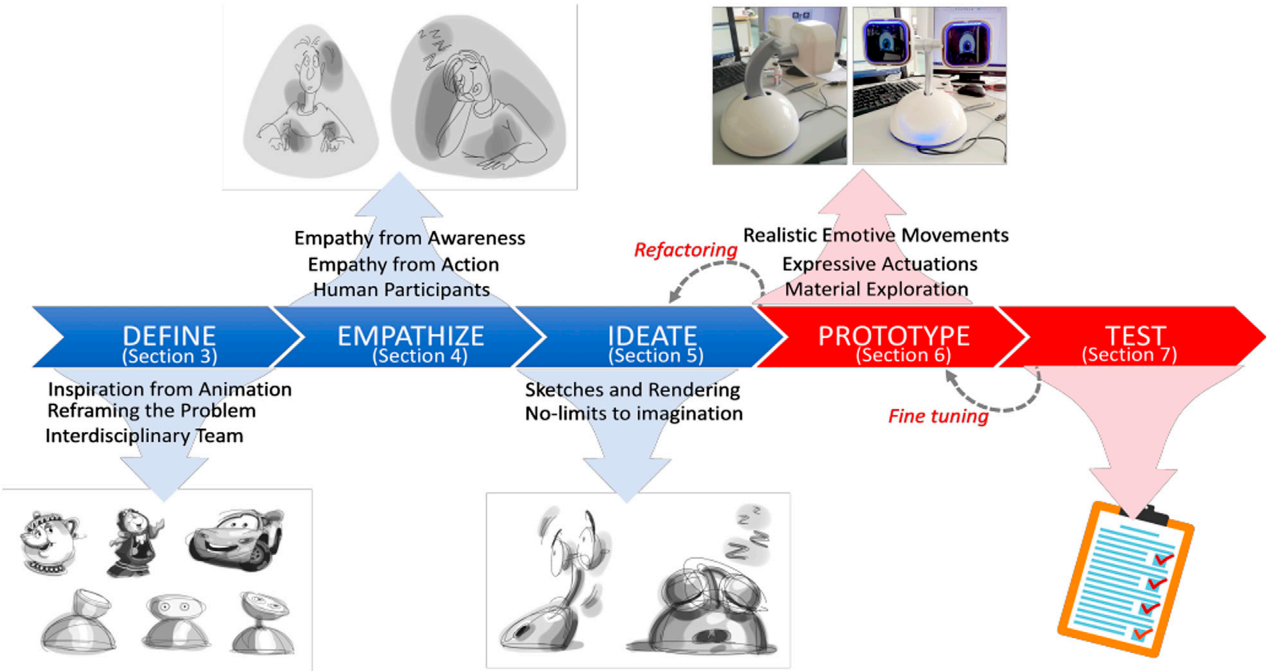

FIGURE 2 | Design Thinking process adopted for the development of Haru Beta.

followed "an analytic and creative human-centered process" that cycled through stages involving "reflective thinking, productive action, responsible follow through and re-framing of the design problem" (Gomez et al., 2018, 235). An analysis of the design process for Haru Beta, focusing in particular on the Define and Empathize stages, follows. This identifies the perspectives on communication the process has a tendency to privilege. As will be explained, the human-centric nature of such a process has a tendency to reinforce the decision to make this robot communicate in ways that can easily be interpreted as familiar caricatures of human bodily and facial expressions (as well as potentially relying on readings of robots in relation to people's prior experience of popular cultural texts, their pets and other animals). Later in the article, the benefits of complicating and extending this decision, in particular when a robot is expected to take part in interactions that are engaging for people over the long term, are considered.

Define: Identifying the Initial Problem for Haru as a Communicator

As mentioned above, the project team pre-defined the initial problem they needed to address; how to create "an emotive, anthropomorphic tabletop robot" capable of sustaining "long-term human interaction" bearing in mind the likely build constraints for this machine, affecting the final look and feel of the robot, as well as its motion affordances (Gomez et al., 2018, 235). It is notable that the idea the robot should be "anthropomorphic" was stated up front, although the team was nonetheless concerned to retain an open mind as to the possibilities for the design, without becoming too bogged down in the likely physical issues of realizing this. Following the identification of the high-level goal, the Define stage continued by asking animators to produce sketches of various ways that Haru's design might achieve this goal. This stage therefore drew on the skills of animators in making inanimate objects come "alive". As the sketches in Gomez et al. (2018) show, animated characters from a number of popular films demonstrate how giving objects faces and making them bend and twist in ways impossible for those objects in the physical world creates animated characterizations that can be emotionally expressive in very humanlike ways.

The overarching assumption of this design path is that the expression of emotions via a recognizable face, most often with two eyes and other features that can be identified as eyebrows and a mouth, will help support easily read affective, and as a result engaging and effective, communication between human and robot. While Haru's design team sought to "step away from a literal humanoid or animal form" (Gomez et al., 2018, 235), the anthropomorphic shaping of the resulting design is nonetheless very clear. As **Figure 1** shows, Haru beta's design includes two expressive eyes, animated on thin film transistor displays, with separate light emitting diode strips above that act as colored eyebrows. The eyes can be tilted, and each one can rotate and move in and out in relation to its casing. Finally, a light emitting diode matrix in the robot's body is used to display a colored mouth of various shapes.

As well as supporting an anthropomorphic design path, the process of considering particular animation styles and techniques for normally inanimate objects in films and cartoons also shapes this robot's communication in strongly sociopsychological terms. The sociopsychological tradition of communication theory regards communication as a form of information transfer, where the aim of the sender of a message is to persuade the receiver of something (Craig, 1999). In terms of robot design, this can be linked with the development of robots that can express emotions and are therefore likely to draw people into interactions often by being "cute" as seen with Kismet (Turkle et al., 2004) and Jibo (Caudwell and Lacey, 2019). Along similar lines, it is easy to see how Haru could also convey a cute personality.

The use of a cute aesthetic has been shown to work well to attract people's attention toward interacting with a robot in the short term (Breazeal, 2002), but questions have been raised over how well this might work in the long term (Menzel and D'Aluiso, 2000; Caudwell and Lacey, 2019), the goal of the Haru project. In addition, although Haru has been categorized in some reports as designed for entertainment, where a cute personality might be particularly engaging and non-threatening (Zachiotis et al., 2018), this would likely not be appropriate when Haru is positioned to complete practical or business oriented communicative tasks. As discussed in more detail below, framing Haru's appearance, expression and resulting personality using the Japanese term "kawaii" might offer a wider range of ways to consider this robot, not simply as cute, but also as playful, inquisitive and surprising, personality traits that might lend themselves to a robot positioned not just for entertainment, as well as suggesting how Haru might engage people in the long term with a personality that develops and changes over time.

Having come up with an overall concept for Haru, supported by a high-level goal and set of sketches showing Haru as an animated character, the team moved on to consider how Haru's nonverbal communication would work in more detail. In particular, they were concerned to explore how Haru might express a variety of emotions at different levels of intensity and in ways that a wide range of people would recognize.

Empathize: Expressing Emotion for/as Haru in Communication

In the Empathize stage of the design process, Haru's design team worked with a set of volunteers, designated as performers. Having been shown the initial set of sketches for Haru from the Define stage, these people were asked to use a combination of body language and facial expression to act out particular emotions as they would themselves, and also as they imagined Haru would (Gomez et al., 2018). Although the Empathize phase of a Design Thinking process often involves empathizing with users, it is interesting to note that here the idea of asking users to try to empathize with the robot was also important, since this outcome will be a key part of Haru's success. Video feedback was provided to the performers, and coaches gave instructions to help them express emotions across a range of different intensities (Gomez et al., 2018). Again, the strongly human centered nature of this process, with a focus on coding human expressions of emotion as well as asking humans to think themselves into the robot's body imaginatively and mimic how the robot might emote, continues to support the anthropomorphic nature of Haru's design. From a sociopsychological perspective, this robot is expected to attract attention and then persuade people to take part in continued interaction through its emotionally expressive communication and personality.

This process, involving the performance of emotional expressions, can be linked with François Delsarte's method for acting, which is based on a close "analysis of facial and bodily gesture" to identify specific movements that can be reproduced to operate as an expressive language easily interpretable by an audience (Maltby, 2003, 400). In terms of communication theory, such an approach not only works in relation to the persuasive, sociopsychological perspective discussed above, but also supports how this style of emotional expression can be part of cybernetic-semiotic exchanges coded in intersubjective (catering in this case for human and robot understanding) language or other signs (theoretical structure from Craig, 1999, developed in Sandry, 2015). From a cybernetic-semiotic perspective the precise nature of the message and its clear encoding is key. Even without considering the use of verbal language, Delsarte's approach to acting relies on a performer's ability to code emotions into readily recognizable nonverbal facial and bodily expressions that precisely communicate specific emotional responses. For Haru's design team, identifying ways to code emotion across a number of human bodies and faces assists in programming the robot to read people's emotional state during an interaction. Then, asking performers to empathize with Haru, putting themselves in the robot's place to act out how they think it would express an emotion, supports the design of the robot's expressive eye animations and movements of its eyes, eyebrows, neck and mouth.

Realizing Haru Beta in Physical Form Through Ideate, Prototype and Test Phases

The human-centered Define and Empathize phases of Haru's design process drove a strongly anthropomorphic conceptualization for Haru. The importance of supporting anthropomorphism continued into the Ideate phase of project, with its focus on finding imaginative solutions to make Haru as expressive as possible, setting aside likely practical limitations for a physical robot. At this point sketch artists built upon the early sketches for Haru created in the Define phase to show the potential for the robot to express emotions inspired by the findings of the Empathize process. These sketches reinforced the anthropomorphic shaping of Haru throughout the design process, and also clearly raised some challenges for the physical prototype.

While a sketch artist can stretch and squash a robot's body in extreme ways that reinforce particular emotional expressions, this is difficult to realize for a physical robot that already has a relatively complex design. The Prototype phase therefore necessarily involved an iterative process, through which the ideas developed during ideation were taken seriously, but also refactored in light of the limitations of the physical and engineerable form the robot would take. Following the development of a prototype, a Test phase allowed the performance participants to offer feedback on the design enabling further refinement. As Gomez et al. (2018) note, this phase was not meant to encompass a full user interaction study, but rather was an integral part of the initial design process to test the effectiveness of Haru's emotional expressions.

Design, Art and Communication as a Science

The development of Haru Beta made good use of a modified Design Thinking process to shape and coordinate the work of an interdisciplinary team, including those with skills in visual and performing arts. In particular, the artists' conceptions for the expressive possibilities of this robot, as well as the ability of performers to produce their own expressions, and expressions "as Haru", provided a depth and complexity to conceptions of this robot as an expressive communicator. These then had to be tempered by roboticists as engineers well aware of the physical constraints of building a robot.

Although design and art were key to Haru's development, the analysis above shows how the robot's resulting communication can nonetheless be framed in scientific terms, as precise, clearly coded and reliably persuasive for anyone with whom it interacts. It would seem to make a great deal of practical sense to design and develop with sociopsychological and cybernetic-semiotic communication success in mind. Such a focus is easily judged likely to create a robot that is compellingly cute, familiar and easy for humans to interact and communicate with.

EXTENDING A BROADER CONCEPTION OF HARU'S POTENTIAL AS A COMMUNICATOR

However, thinking about human-human communication, let alone human–robot communication, in anything other than the simplest situations highlights the difficulty of perfectly coding precise messages, or of reliably persuading the other, because the majority of communicative events involve some level of ambiguity, together with the potential for misunderstanding. Indeed, scholars have argued that ambiguity and misunderstanding are actually an intrinsic part of any worthwhile human communication (Bennington, 1994; Chang, 1996). While ideas of communication as a scientific and perfectible process might be attractive, it is therefore also useful to embrace the art involved in communication that recognizes the value of a more relational and dynamic understanding of communicative processes within which one must also acknowledge the impossibility of comprehending the other completely.

This idea is emphasized by the phenomenological tradition of communication theory for which any attempt to *know* or understand the other fully is fraught with difficulty. Instead, a phenomenological perspective emphasizes the other's difference from the self as a chasm that cannot be bridged by an empathetic stance (Levinas, 1969; Craig, 1999; Pinchevski, 2005). This perspective raises questions not only in relation to understanding the communication of a robot such as Haru, but also for the design process discussed above, which asks performers to empathize with Haru and act out how this robot might express a particular emotion. It is therefore good to note that when working with the results of the Empathize stage, Haru's creators embraced the way this robot's eyes and neck had the potential also to express with movements similar to a person's hands, arms and shoulders (Gomez et al., 2018). This opens up broader possibilities for Haru's expression to be both *like* that of a human, and also *fundamentally different* (given its very different form and potential to express in non-humanlike ways that are nonetheless read by humans as communicative).

The more philosophical take on communication offered by phenomenological theory conveys an idea of otherness that is not only open to the difficulties of making a robot with non-humanlike form express in humanlike ways, but also one that suggests a robot other's difference is an integral part of why one might communicate with it as opposed to a problem that must be overcome (Sandry, 2015). Framing the initial moment of meeting as an encounter with otherness draws out the importance of difference as a means not only of attracting attention, but also retaining attention over the mid to long term. As Caudwell and Lacey suggest (2019, 10), it may well be important for social robots to "maintain a sense of alterity or otherness, creating the impression that there is more going on than what the user may know", because "this sense of alterity (real or simulated)" is one way to break down "the strict power differential that is initially established by their cute aesthetic". In this way, a social robot can become more than a compliant communicator always focused on responding to human queries and questions; instead, such a robot can be recognized as having the potential to act on its own, provide information or call for human attention and response as it requires.

Framing Haru as "Kawaii"

Extending these ideas further, rather than framing Haru's personality and expressive ability as "cute", as mentioned above, it may be more productive to adopt the Japanese term, "kawaii". Although this term is often translated as, or at least closely associated with, the English word "cute" and its meaning (Cheok and Fernando, 2012), describing Haru as kawaii draws attention to this robot's potential for playful communication, approaching things with what seems to be "an inquisitive attitude" and the ability to surprise users in interactions, catching them "off guard" (Cheok and Fernando, 2012, 300). The idea of Haru's ability to surprise people resonates with the importance of "interruption" in phenomenological perspectives on encounters between selves and others (Pinchevski, 2005; Sandry, 2015). Even as self and other are drawn into the proximity of an encounter, "the face to face", the other's alterity is always a factor (Levinas, 1969). From this perspective, Haru retains the potential to interrupt or surprise people by expressing itself as a social, communicative, other-than-human presence. As opposed to being non-threateningly familiar, Haru thus has the potential to be quirky and unusual, drawing people's attention and inviting their participation in continued communication. Alongside the potential to be surprising though, Haru's small size relative to humans (even a human child) and the robot's fixed positioning nonetheless mean this robot is unlikely to scare anyone away.

It should be noted that defining Haru as kawaii, or even as having kawaii characteristics, is complicated by the fact that different people, and even the same person across changing circumstances, may or may not choose to appraise the same object as kawaii (Nittono, 2016). Even while a kawaii robot might be a more intriguing communicative partner than one regarded simply as cute, there is likely still a delicate balance between it being delightfully quirky, or irritatingly inappropriate. The shifting attribution of the term kawaii depending on the preference of individual people and changes in context for encounters with Haru raises the importance of considering a sociocultural perspective on communication in human interactions with this robot. This perspective analyses communication as a means of producing, reproducing, and negotiating shared understandings of the world (Carey, 1992; Craig, 1999). From this perspective, communication is heavily reliant on the overarching cultural setting as well as the detailed context of an interaction between particular individuals. The space within which people interact with Haru, the framing of the robot's purpose, how familiar a person is with the robot, the presence of other people that can see and hear the interaction as bystanders, watching someone else interact with the robot, previous experiences with interactive technologies and many other factors may well have an appreciable effect on how people will respond to the robot (a number of these factors being raised in Lee et al., 2010). Some of these contextual elements can be thought of in terms of narratives, including stories told to situate Haru in relation to a particular communicative scenario, the stories that may emerge in interaction and also the stories that people see played out in other's interactions with the robot, or those they hear other people recount about their experiences with the robot. The importance of context, and the idea of changing appraisals of a robot, also highlights how human–robot interactions are dynamic, not just within the interaction itself, but also in relation to the situational factors that surround that interaction. It is not only the story that emerges within an interaction that is important, but also the surrounding stories that shape and frame the interaction in particular ways.

Communication as a Dynamic Process Occurring in a Dynamic System

A consideration of sociopsychological, cybernetic-semiotic, phenomenological and sociocultural perspectives on interactions with Haru suggests that it is useful to adopt a more dynamic understanding of communication overall, which could be important across design and prototyping contexts, as well as in planning user interaction studies with robots. In particular, although Delstarte's idea of coding emotions for performance is a practical part of the design process discussed in this article, considering how emotional communication can emerge through dynamic interchanges highlights the potential for an alternative acting paradigm to play a part. This alternative view is typified by the Stanislavski technique, within which performers are expected to coordinate with one another in the moment of interaction, behaving in ways shaped as reactions or responses to other performers (Moore, 1960; Hoffman, 2007). When human–robot interactions are considered from this perspective, the precise coding of emotion or of information becomes less important than the ability of the robot to respond to changes in its environment as well as to the particular person with which it is currently engaged in interaction.

From a dynamic systems perspective, communication is not about the transmission or exchange of fixed pieces of information, because, as Alan Fogel argues, "information is created in the process of communication", such that "meaning making is the outcome of a finite process of engagement" (2006, 14). This shifts a cybernetic-semiotic focus from a preoccupation with clear and precise messages, to considering the value of iterative exchanges of feedback and response through which meaning emerges (Sandry, 2015). It also reinforces the idea that sociopsychological persuasion may rely not so much on any fixed perception of "cuteness", but rather on reading a personality that develops and changes within and between interactions. Finally, a focus on dynamic communication, or communication as a form of "dance" (Shanker and King, 2002, 605), draws attention to the potential for nonverbal, embodied communication to support exchanges that are not restricted by turn-taking, but rather become continuous processes "within which signs can overlap even as they are produced by the participants" (Sandry, 2015, 69).

Although it would have been difficult to assess the dynamics of particular interactions with Haru in the early stages of the design process discussed above, this approach should become easier to plan for and to apply once a working prototype becomes more widely available to allow people to test what it is like to interact with Haru directly. In addition, while the development of Haru Beta has concentrated on designing the robot's body to allow expressive emotional communication, this robot will also need to communicate flexibly in a range of other ways if it is to fulfill the goal of being a platform to support human–robot communication research more fully.

Developing Haru's Communication across "a Triple Audiovisual Reality"

The conception of Haru's potential as a flexible, dynamic communicator developed above identifies the need to incorporate more communicative skills for this robot than the nonverbal expressions developed for Haru Beta. Overall, the development of Haru, as a social robot for long term interaction, is likely best driven by a broad understanding of what constitutes communication as "a triple audiovisual reality" (Poyatos, 1997). This idea is drawn from research into the complexity of simultaneous translation, which emphasizes the need to attend to not only the words people use, but also a range of communicative elements that surround those words, in order to come close to an accurate translation of what someone is saying. The triple structure, when concerned wholly with human communication, consists of verbal language (speech itself), paralanguage (tone of voice, nonverbal voice modifiers, and sounds), and kinesics (eye, face, and body movements) (Poyatos, 1983).

From this perspective, Haru Beta's communication design focuses entirely upon kinesics through its eye animations and movements, eyebrow colors and shapes, neck movements, and colored light displays on its body. It should be noted that in some cases the kinesic communication of the robot amounts to a direct communication signal, such as a red down-turned mouth on its body, combined with frowning eyes and red eyebrows, which can be read as a clear coding for anger (drawing on Delsarte's ideas on communicating emotion through acting). In contrast, some of Haru's other kinesic expressions may be less obviously coded, more ambiguous and open to interpretation on the basis of context. This applies in particular to Haru's more complex emotional expressions shown in **Figure 1**, such as shyness and curiosity. Currently, the animation of Haru's eyes offers the most flexible mode of expression, but attempts to make the robot's other features more subtly expressive may be made in future.

Haru's continued development has involved the introduction of a voice interface, although the exact voice Haru uses could be refined on the basis of user-interaction studies. With its vocal capabilities, Haru can communicate across the triple structure in face-to-face situations in language and using expressive sounds, as well as through its body movements. Haru's other-than-human form also has the potential to support completely novel modes of communication, such as expressing emotion through colored lights, the ability to project content onto a wall or screen, and maybe other forms of body language (dependent on the final form of the robot).

Considering the Art of Communication in Relation to Robots such as Haru

In spite of the fact that creative art and design played a key role in the development of Haru beta, the goal of creating an easily anthropomorphized, communicative robot was linked earlier in this article with scientific ideas about precisely coded emotional expressions that support both sociopsychological and cybernetic-semiotic understandings of this robot's communication. More recent sections of the article argue that more complex communication scenarios likely involve ambiguity, the potential for misunderstanding, and the need to adopt a more dynamic understanding of communication during which meaning emerges over the course of an interaction. This idea might be particularly important for robots designed to communicate with people over a sustained period or on a number of separate occasions.

The question of how a robot might encourage people to interact with it repeatedly or in the long term is not simple to answer. Guy Hoffman (2019), for example, when considering robots designed to share people's homes identifies "clear technological barriers" in relation to both "realistic non-repetitive gesture generation" and "dialogue algorithms" that make supporting sophisticated interactions over time difficult. This is clearly an important consideration for social robots more generally (whether in homes, workplaces or social spaces). Rather than assuming that robots need to be more complex or intelligent, Hoffman argues that social robot development needs artists, "professionals who excel at storytelling, emotional engagement, and structured repetition" (2019). In particular, Hoffman goes on to identify the value of taking seriously the development of stories within and around interactions between humans and robots.

These ideas are being put to the test as Haru's development continues, with the team actively exploring how the development and performance of "captivating storylines" might help a robot to attract people's attention and encourage engagement over the long-term. The idea of content creation for Haru in part relates to developing stories Haru might tell people, potentially projecting graphics onto nearby surfaces. While Haru might well tell stories designed to entertain, alongside this the idea is for Haru to share its own story, giving people a sense of Haru's internal life and imagination, potentially adding creative depth to people's sense of Haru's existence and personality. The content Haru projects onto surfaces, for example, will therefore be designed not to reduce people's attention to Haru, but rather to complement Haru's presence, giving the robot a context from which to be understood, a meaningful back-story. The importance of back-story can be seen in the development of other robots, such as Fish and Bird based on characters from a Greek myth (Velonaki et al., 2008), for which a story not only supports the development of the individual characters of the robots, but also helps to explain their interaction with each other for visitors to their installation space. In the case of Haru, the idea of content creation in the form of storytelling is expanded. This robot is able to tell its own story, as well as stories designed to entertain, but, maybe more importantly, people's interactions with Haru are also thought of as creating their own stories that develop over time.

The move from understanding communication as a process of coding signals, whether in language or through nonverbal sounds and signs, to viewing communication as a dynamic and constantly emerging interchange between communicators (whether human and human, or human and robot), can be framed as a move away from scientific ideas about communication as a perfectible process and toward acknowledging the art of communication. Historically, it is the rhetorical tradition that regards communication as the "practical art of discourse" (Craig, 1999, 135), but it has been argued that "there is considerable overlap between the rhetorical tradition and others" allowing this idea to be extended to communication as defined more broadly (Littlejohn and Foss, 2011, 62). From this perspective communication is less about a fixed message and more about a developing story, where conversations can link back to previously shared experiences, such that memory and the continual emergence of new meaning combine to support interactions perceived as valuable over the long term.

FUTURE SCENARIOS FOR RESEARCH WITH HARU TO EXPLORE COMMUNICATION IN CONTEXT

At this point, two overarching scenarios are being developed and implemented to drive future phases of research with Haru. The first of these positions Haru as a robot that supports a new form of hybrid telepresence. In this scenario, the initial emphasis will be on using Haru as a novel interface, to add a level of expressiveness when someone at a distance is communicating through the robot using either text or voice. Clearly this is most important when the person communicating cannot provide a video feed; however, even when a video feed is supported, it can be argued that the addition of a means to support gestural and body language could enrich telepresence, in particular when the telepresence user is trying to communicate with a group of people (Stahl et al., 2018). Development of teleoperation interfaces for Haru serve a double purpose, allowing research into how this type of affective robotic platform can extend a person's telepresence without or alongside a video display, but also providing the opportunity to test the range of Haru's expressiveness prior to developing its capability for autonomous operation, the second scenario for research with Haru. In this scenario, Haru becomes a communicator in its own right. Whether Haru is positioned in a home, workplace or other social context, the aim is that the robot will communicate in a way that is immediately engaging and conveys a sense that it has a clear personality. As this article has discussed, the idea is that people want to communicate with Haru not only on first meeting the robot, but also on subsequent occasions, such that they are drawn into long-term interaction. At times, Haru's ability to communicate pertinent information clearly will be vital, but the development also embraces a broader idea of communication that encourages people to respond to the robot as an entity with which they are happy to engage on many occasions.

Haru as a Negotiator and Mediator Assisting People in Telepresence Communications

When positioned for telepresence, unless two Haru robots are in use, one person's encounter with Haru will be mediated through a smart device or computer interface, whereas the other person will interact directly with the robot. This scenario therefore involves development and testing of a digital interface for Haru, where the suggestion is that text and speech will be augmented through the use of "Harumoji", emoji that convey Haru's particular embodiment and expressive style. Harumoji might well be used to help the person at a distance control Haru's physical expression, to add depth to the expressive quality of the communication possible through the telepresence interaction with the person in front of the robot. In considering this scenario, there is a sense that the person with Haru will already be familiar with the robot, its form and embodied communications. This highlights an important question for experiments with Haru for this scenario: how will Haru negotiate the move from *communicating with a person as itself*, for example to gain their attention and let them know someone wants to communicate with them, to *communicating as the person calling from a distance*? While the narrative frame to initiate people's understanding of Haru as a telepresence assistant might seem simple, the narrative within the interaction itself will need to negotiate gracefully the changeover from Haru expressing its own agency and communicating for itself in interaction, to Haru providing a telepresence service, expressing and communicating on behalf of a person, and back again once the telepresence call is complete.

It is worth noting that for this scenario, the novel communication channels Haru might support, such as projection onto nearby surfaces, could either be used to support video of the person communicating at a distance, or may prove more useful when displaying materials being discussed in the conversation. The potential of the embodied aspects of Haru's communication are really the key element of this scenario, designed to explore how Haru's expressive physical form could be used to add depth to, or complicate, the communication of emotion in someone's tone of voice through its expressive eyes, eyebrows, neck and mouth. Importantly, as mentioned earlier in this article, the design process for Haru also identified that this robot's body, in particular the eyes and neck, can convey a sense of a person's expression via hands, arms and shoulders. In this scenario, a level of human control over the robot's expressive communication would be maintained much of the time, so it offers the opportunity to explore Haru's potential as a communicator through a wizard-of-oz process that is not hidden from human participants, but rather is overtly presented as part of the experiment.

Haru as a Communicator with People in its Own Right

Working to extend Haru's control of its own communication (in part developed through working with Haru for telepresence) subsequent scenarios will be concerned with building Haru's ability to develop and express a personality, whether Haru is positioned as a receptionist for a business, information provider in public spaces, or operating in the home as a personal assistant or companion. In smart homes and workplaces, Haru might also be integrated to assist with managing systems and devices in the surrounding environment. The eventual aim will be to enable development and expression of a personality associated with Haru's robot agency, which will make this robot seem somewhat "alive" to people during an interaction. Overall, the goal is to support Haru's ability not only to communicate, but also to build relationships with people over time, as the robot interacts and collaborates with them in shared activities.

As mentioned earlier in this article, while Haru might be relatively successful as a "cute" personal assistant in the home, this type of robot has not yet proved successful (the examples of Jibo and Kuri, also discussed by Hoffman (2019), spring to mind). It may be that Haru would be better off with a personality that conveys more depth even during the initial encounter, and certainly one that develops beyond that framing over time. In business, workplace and public settings where Haru is positioned as providing a service, whether as a receptionist or information provider, it is likely that in most contexts people might prefer to meet Haru as friendly in professional, as opposed to personal, terms (Sutherland et al., 2019). This is something that a cute aesthetic might not support that well at all. In addition, Lee et al. (2010) note that different people are likely to encounter the robot in different ways shaped by their previous experience. While some will be open to taking part in a friendly conversational exchange, others might prefer to treat Haru as an information providing machine, with no need to engage in social niceties. This may pose a challenge for Haru's communication style, although the clearly socially communicative nature conveyed through its form for anyone encountering this robot even for the first time, may go a long way to encourage friendly interactions on most occasions.

Whether Haru operates in a home, workplace or public space, it is likely that this will require communication not just in response to an initial encounter, but also over time with people who frequent the space the robot occupies on a regular basis. An exploration of how operation over the long term might best be supported is one of the core reasons Haru has been developed. Other studies of robots positioned in a space over the long term provide some insights. In particular, Simmons et al. (2011) identify the need for the robot to have a background story, and also some sense of a life story that can be revealed over time. This provides a context for the robot's actions and also supports how they might change over time, this change being important in sustaining people's interest and engagement with the robot in the long term.

As discussed in a previous section, Haru's project team has noted that the potential for Haru to project images onto surfaces might become a part of an embodied communication of Haru's background story that could also provide a sense of life story over time. In addition to Haru being positioned in physical spaces with people, this robot could also project and interact with its own virtual world. Haru's interactions with its virtual world would be used to reinforce the sense that Haru is somehow "alive", even when it is not taking part in an ongoing interaction with a person, allowing people's perceptions of its personality to develop along with the visual story the virtual space supports. From a wholly practical perspective, Haru's interactions with this virtual space would also allow clear communication of when Haru's attention is on its world (the projection being brighter and in focus) and when Haru turns its attention to a nearby person (the projection becoming faded and out of focus).

Exploring the Shifting Sense of Agency in Communication with Haru

Haru's communication with people across the scenarios described above, from telepresence to robotic agency taking part in shared activities across different contexts, can be understood from all the different communication-theoretical perspectives introduced in this article. Initially, meeting Haru can be framed as an encounter, which invokes the sense in which Haru expresses a personality, an otherness and also a level of apparent agency. At times, addressing Haru's ability to communicate precisely and clearly in cybernetic-semiotic terms will be vital, in particular when Haru needs to provide someone with information directly. At other times, Haru's communication might be quickly understood from a sociopsychological perspective, for example as the robot attempts to persuade people to interact with it in particular ways through its expressive communication, most likely trying to elicit a friendly and sociable tone. As Haru is embedded in particular contexts (such as being a receptionist or personal assistant), but even before this with Haru firmly positioned as a robot people meet through laboratory experiments, a sociocultural perspective on communication draws attention to the specific context and the details of how Haru is situated alongside the people with which it interacts. An understanding of Haru's communication may well be shaped by people's existing expectations of a social robot, but the real task may be to allow Haru to build on those expectations to enable new ways to communicate, developing people's sense of its unique personality and ability to take part in shared activities with them. This leads to the importance of supporting Haru as seeming to be, at least somewhat, "alive", a social being which people initially encounter and also continue to want to interact with, as a potentially surprising other from a phenomenological perspective, but also as an other that has its own life story conveyed through a novel, embodied communication channel involving projected content.

Methodologies for Gauging the Success of Haru's Communication in the Long Term

An exploration of Haru's potential as a communicator, and the potential for human–robot communication more broadly, can clearly be driven from a number of experimental and analytical directions, including those that draw on techniques and methods from psychology, human–computer interaction (HCI) and human–robot interaction (HRI) studies. The Haru project team also recognize that these can be complemented by a humanities perspective, in particular when the goal is to assess how human–robot communication might develop over an extended period of time.

When considering the potential for research considering long term HRI, for example in a person's house, it has been noted how "few studies have investigated the long-term use of technological systems in home environments", meaning "the traditional technology acceptance literature lacks a profound body of long-term research" (de Graaf et al., 2018, 2583). It is clear though that such research would be valuable across any context where a human and robot were expected to interact in the long term, since it seems likely that "the development of user experiences with a technology or gaining user skills might change the user's attitudes toward, uses of, or even the user's conceptualizations of that technology" (de Graaf et al., 2018, 2538 citing a number of research studies in relation to each of these potential changes). One of the reasons for the lack of long-term HRI research studies may well be that "robot technologies are generally not robust enough to be studied outside the lab for extended periods of time without supervision of an expert" (de Graaf et al., 2017, 224). As a research platform, not a commercial robot designed for consumers, this is clearly an issue faced by researchers using Haru, but a consideration of long-term interaction is explicitly stated as one of the project's goals. One way to carry out this type of research is to engage with humanities methodologies, such as autoethnography. As the "auto" prefix suggests, the advantage of pursuing this methodology in particular is that the robot remains in the care of the researcher.

While humanities methods tend not to offer quantitative measurements as results, their value is in the added depth and breadth of understanding they provide by developing theoretical and qualitative explanations of what happens in and around human–robot interactions. For example, adopting an autoethnographic framework for research with Haru will allow the researcher to write about their own experiences with the robot, developing detailed "thick descriptions" of what it is like to interact with and through Haru. This type of research can be conducted over a planned period of time that might span a few days, weeks or months. Although autoethnography is not often used as a methodology for HRI or social robotics research more generally (Chun, 2019), there have been some recent exceptions. For example, Verne (2020, 41), writing about adapting to using a robot lawn mower, explains how "autoethnography as the methodology gave rich access to events and personal experiences", valuable because "personal thoughts and reflections were important for understanding how [they] changed [their] goals and values while adapting to the robot". Clearly this idea resonates with the potential de Graaf et al. (2018) see in carrying out long-term research projects, while also mitigating the potential lack of robustness in the robotic platform. The use of thick description is also open to noticing and documenting all elements of the interaction with Haru, including the initial and subsequent encounters with the robot as an other, the stories that are told in and around interactions with and through the robot, as well as the details of the embodied dance of communication that any interaction with Haru will entail.

Although some researchers might argue that such research has limited use, since its "findings cannot be extrapolated to larger populations" (James et al., 2019, 2.8), it can certainly drive future research involving participants interacting with Haru, forming the basis for observational studies as well as semi-structured interview questions for participants (the latter being a use James et al. (2019) acknowledge). In addition, the published research of Verne (2020) discussed above, as well as positive reviews of larger projects such as *Seeing like a Rover*, where thick description is used to convey the responses of mission scientists to mars rovers (Vertesi, 2015), highlights the value of this type of qualitative observation and recording of people's responses to robots in its own right.

CONCLUSION

As this article has shown, adopting a Design Thinking methodology for an interdisciplinary team of animators, performers, sketch artists and roboticists, embraces ideas from both design and art. This design path results in the creation of a robot that is strongly framed as anthropomorphic, potentially also with a cute aesthetic. During the design process, there is also likely to be a focus on the robot's sociopsychological and cybernetic-semiotic communication capabilities, theories of communication that can be associated with scientific ideas of communication as a perfectible process of precisely coded information exchange or toward successful persuasion. However, drawing on phenomenological and sociocultural theory, and employing the idea of a robot as kawaii as opposed to cute, provides a broader conception of the potential for Haru as a communicator open to a more relational and dynamic understanding of the art of communication, within which it is vital to respond to the other and their difference from the self. This is further reinforced by engaging with ideas of communication that encompass language, paralanguage and kinesics. This triple structure is important during initial and repeated encounters with Haru, as well as in relation to the sociocultural, ideological and narrative contexts, or stories, in and around that interaction. Acknowledging communication as more than language also highlights the importance of embodied and dynamic approaches that position communication as a dance of interaction.

As a platform for communications research, it is clearly important that Haru's design not only lends itself to the broad analysis presented here, but also that the development team will use that analysis to drive future research and potentially also new design decisions. This article's argument suggests that there are benefits to considering communication theory of many types in all robot developments to support the creation of machines that are flexibly able to communicate in many different ways, and that have the potential to be interesting communicative companions even in the long term. The article has also highlighted how humanities research methods, with a focus here on autoethnography, offer valuable qualitative techniques that can complement and extend the quantitative methods more often used in research that investigates human interactions with robots.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The majority of the drafting and editing of this article was completed by the first author, ES. RG and KN reviewed early drafts and provided essential feedback that assisted further development of the article. In particular, they highlighted the potential of considering the term "kawaii" in relation to Haru's design, development and implementation. ES and RG are currently collaborating to develop research projects with Haru, with a particular focus on studies that use humanities-based, qualitative research methods to consider communication with Haru across both scenarios discussed in this article.

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The Aesthetics of Encounter: A Relational-Performative Design Approach to Human-Robot Interaction

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This article lays out the framework for relational-performative aesthetics in human-robot interaction, comprising a theoretical lens and design approach for critical practice-based inquiries into embodied meaning-making in human-robot interaction. I explore the centrality of aesthetics as a practice of embodied meaning-making by drawing on my arts-led, performance-based approach to human-robot encounters, as well as other artistic practices. Understanding social agency and meaning as being enacted through the situated dynamics of the interaction, I bring into focus a process of *bodying-thinging;* entangling and transforming subjects and objects in the encounter and rendering elastic boundaries in-between. Rather than serving to make the strange look more familiar, aesthetics here is about rendering the differences between humans and robots more relational. My notion of a relational-performative design approach—*designing with bodying-thinging*—proposes that we engage with human-robot encounters from the earliest stages of the robot design. This is where we begin to manifest boundaries that shape meaning-making and the potential for emergence, transformation, and connections arising from intra-bodily resonances (*bodying-thinging*). I argue that this relational-performative approach opens up new possibilities for how we design robots and how they socially participate in the encounter.

Keywords: human-robot interaction design, aesthetics, performativity, agency, design, movement

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INTRODUCTION

Social robots are designed to operate, mediate, or directly engage in social scenarios, provoking the question of how a machine becomes a social participant in these encounters. "Good" interaction, it is often assumed, should feel "natural," i.e., reminiscent of social interaction between humans (Hegel, 2012; Dautenhahn, 2013; Lindblom and Alenljung, 2020). But what if "there is no such thing as 'natural interaction'" (Dautenhahn, 2013)? Human social interaction is a complex dynamic phenomenon, embedded in a specific cultural setting, shaped by environmental and social contexts, and reflective of lived experiences and relationships. Given robots' vastly different mechanical and cognitive makeup and, not least, complete lack of "lived experience" (Dewey, 1934), the notion of "natural" in the context of robotic artifacts is even more problematic. Mindell thus argues that it is the designer's beliefs and intentions that shape a robot's "abilities and its relationships with the people who use it" (2015: 10). In other words, a robot's social competences are not "natural" but shaped by the designer's beliefs of what "natural interaction" looks like. The challenge of human-machine communication, according to Suchman, lies in the differences and "deep asymmetries" between humans and machines "as interactional partners" (2007: 11). Yet "obscur[ing] enduring asymmetries," e.g., through humanlike features or behaviors, does not resolve them and "people inevitably rediscover those differences in practice" (Suchman, 2007a: 13). While modeling human-robot relationships after human relationships (Jones, 2018; see also Castañeda and Suchman, 2014; Hegel, 2012; Dautenhahn, 2013) may ensure a certain familiarity in our encounters with robots, mimicking our social relationships with these new social entities can also only be just that: a figment of our human imagination curbed by what we already know—or assume to know—about the human and being social.

This article introduces an alternative, arts-led approach to imagining our relationships with robots that embraces their difference and aims to take on a mediating role between human interactors and these potentially new social entities by locating itself in the middle of the encounter. My Machine Movement Lab (MML) project opens up an intimate link to performance-based inquiries into the relational enactment of human-robot encounters to investigate the generative potential of movement and its dynamic qualities to enact meaning with abstract robotic artifacts. Starting in 2015, the practice-based research project set out to explore the possibility of meaningful encounters with robots in ways that playfully employ machines' unique otherness. To situate[1] such strange artifacts in our social environment, we explore the potential of qualitative movement dynamics, "com[ing] to the fore in dance" (Sheets-Johnstone, 2012: 49), that afford them a relational quality that is unique to their machinic embodiment. Importantly, this relationality is not a capacity built-into the robot but rather is generated and comes to effect in the interactional process of each particular encounter. As a designer, positioning oneself in the middle of the encounter and the relationships it produces deliberately undermines focusing on the individualism of interacting agents and, instead, promotes attending to the crisscross of perceptual flows, movement dynamics, and emergent effects that give rise to meaning. This is a fundamentally aesthetic process as I will attempt to lay out in this article, rendering aesthetics core to meaning-making in human-robot interaction.

My notion of aesthetics is not confined to the purview of philosophy and art theory, where "aesthetics experience" is evoked or sustained by an "aesthetics object" and delineated as the appreciation of beauty in all its forms (Osborne, 1986). Cultural theory and other disciplines, in recent years, have worked to realign our understanding of aesthetics with its Greek origins *aisthēsis* (perception), often described as an experience of sensorial or sensate binding, "a connectivity based on the senses" (Bal, 2015: 152; see also Bennett, 2012). My understanding of aesthetics pertains to how we make meaning, arising from particular relations, and patterns thereof, that resonate with us, predicated upon our bodily sense-making of the world. Aesthetics here is a mode of embodied and distributed meaning making (see Johnson, 2018; Johnson, 2007; Lindblom, 2020; Lindblom, 2015), tightly linked to a relational understanding of agency, enacted through the very same relational dynamics (see Barad, 2007; Suchman, 2007a). Bringing into dialogue Dewey's pragmatist aesthetics (1934) and central concepts from embodied cognition, Johnson argues that "all meaningful experience is esthetic experience" (2018: 2). It draws on all the processes by which we make sense of the world and "enact meaning through perception, bodily movement, feeling, and imagination" (Johnson, 2018: 2; see also Alexander, 2013). Meaning is thus fundamentally "relational, experiential, and enactive" (Johnson, 2018: 244), framed in a particular social, material, cultural, and historical context. Looking at meaning-making in human-robot interaction, my proposed esthetic account also draws on a performative[2] understanding of agency, where agency is not a property, held by an individual agent, but rather is "a matter of intra-acting . . . an enactment" (Barad, 2007: 178). The perception of agents or someone/something being perceived as agential then is an effect of agential enactment and inherently relational. Speaking to our representational and differential practices and how they may shape our relationship with robots, the performative is an important dimension in our meaning-making processes, both as part of the design process and interactional experience (see *Bodying-Thinging*).

In this article, I will attempt to lay out the framework for *relational-performative aesthetics in human-robot interaction*, drawing on performative new materialist accounts (e.g., Barad, 2007; Suchman, 2007a; Gamble et al., 2019) and embodied, distributed meaning-making (e.g., Johnson, 2007; Johnson, 2018; Lindblom, 2020; Lindblom, 2015), and grounded in my Machine Movement Lab (MML) project[3] in conversation with other artistic approaches (Demers 2016; Penny, 2016). Aesthetics here is a site of research and both a theoretical lens and a material practice of inquiry into performative, relational meaning-making in human-robot interaction. I begin by discussing positions and practices in and around human-robot interaction research that

[1]By situated (adj.) or situatedness (n.), I refer to something, e.g., an interaction, occurring in a particular situation, and, importantly, the particulars of the situation playing a key role in how the interaction unfolds. Situated here thus means being bound to a particular physical, sociocultural, and historical context. Both, situatedness and embodiment have increasingly become important concepts in cognitive science (see Suchman, 1987; Varela, Thompson and Rosch, 1991; Pfeifer and Scheier, 1999), rejecting traditional cognitive-scientific notions of internal representation and computation in favor of studying the fundamental role of bodily mechanisms and the environment, including interactions with other agents, artifacts, etc. (Ziemke, 2002).

[2]The concept of performativity (adj.: performative) was developed by J. L. Austin to study speech acts and has since then been drawn on and extended by numerous theorists, most notably J. Derrida, J. Butler, D. Haraway, and K. Barad. My esthetic approach draws on Barad's (2003) and Suchman's (2007) account of performativity, albeit the scope of this article does not reach into the important discursive dimensions of gender and labor within the context of social robot design. In particular, my relational-performative approach aims (1) to shift the focus from a representationalist to a performative understanding of agency in human-robot interaction, and (2) to look at human-robot interaction as a practice involved with the making and configuring of boundaries between humans and nonhumans or subjects and objects. Importantly, the adjective "performative," as used here, does *not* refer to the nature of dramatic or artistic performance.

[3]Co-directed with Rob Saunders.

are relevant to laying out my argument (*Relevant Positions and Practices*). Following this, I introduce my MML project and its core method of Performative Body Mapping (PBM) that harnesses dancers' tactile-kinaesthetic expertize to explore the social potential of human-robot relationships as *difference in relation* (*Difference in Relation: Machine Movement Lab*) and how it unhinges and makes elastic subject-object boundaries through a process of *bodying-thinging* (*Bodying-Thinging*). In (*Designing with Bodying-Thinging*), I argue that our meaning-making encounters do not only begin once a robot design is complete and able to partake but is put in motion as soon as we begin to imagine, experiment with, prototype, test, and *make meaning of* the artifact's design. Finally, I briefly discuss my current research in expanded performance-making, (*Dancing with the Nonhuman*), revolving around the negotiation of different perceptual worlds facilitated through Relational Body Mapping (RBM), and complete with a (*Discussion and Summary*).

RELEVANT POSITIONS AND PRACTICES IN AND AROUND HUMAN-ROBOT INTERACTION RESEARCH

One might argue that modeling human-robot relationships after human-human relationships has shown that this mimicking approach has succeeded in rendering robots more acceptable and easier to interact with (Hegel et al., 2009; Dautenhahn, 2013; De Graaf and Allouch, 2013), yet we can also find many studies reporting on the challenges brought forth by this assumption (Lee et al., 2016; Vlachos et al., 2016; Šabanović, 2010). One major concern is that humanlike appearance and behavior often evoke expectations of human-level cognition and empathy, which cannot only lead to frustration (Dautenhahn, 2013) but beguile vulnerable users through an illusory sense of experiencing a mutual relationship (Turkle, 2011). Critical voices from Science and Technology studies have called for "a more differentiated set of starting points for the robot" (Castañeda and Suchman, 2014: 340) that evade generic, universal assumptions about "the human" and could open up other possibilities for human-robot relations (Castañeda and Suchman, 2014). From a creative perspective, such a mimicking approach relies on what we already know—or assume to know—about social relationships and our capacity to form them, posing restrictions not only on what a robot could be but also what relationships we could have with them.

Understanding meaning-making as a fundamentally esthetic and embodied process, situated and unfolding in the interaction scenario itself, moves the design focus into the middle of possible interactional scenarios and puts the spotlight on difference in relation. This relational, performative view contrasts human-centric design approaches founded on the belief that humanlike features and familiar behaviors can be orchestrated to give social agency to a robot (Alač, 2015; Jones, 2017). Social robot design approaches and studies largely limit esthetic concerns to a robot's physical appearance, often specifically referring to its purpose as creating visual appeal (Salvini et al., 2010; Hegel, 2012; De Graaf and Allouch 2013; Hoffman and Ju 2014; Paauwe et al., 2015). The enactment of affordances, which necessarily involves ecological and perceptual considerations that can render evaluation more challenging, is often approached as a matter of an agent's capabilities (Paauwe et al., 2015) or behavioral functions (Hegel, 2012) that can be designed and programmed into a robot (Alač, 2011; Jones, 2018). Human-centric design then becomes a matter of technocentric problem-solving where appearance and capability are viewed as separate design components, rendering the robot a friendly-looking "physical container" (Ziemke, 2016) for social functions.

Coming back to the question of "natural interaction," one major assumption underlying humanlike robot designs is that successful communication "is founded on what communicators already have in common" (Sandry, 2016: 179; see also Boer and Bewley, 2018). It frames social communication as a process that has "a correct outcome" or predefined protocol, where potentially ambiguous meanings or multiple interpretations would be, in Sandry's words, "an undesirable risk that should be eliminated" (2016: 179). But, this desire for control in the interactional exchange may lead to a simplistic, problem-focused approach to social encounters, driven by what makes them "amenable to technological intervention" (Šabanović, 2010) yet blind to the emergent dynamics and effects that are core to our social, embodied interactions. From an embodied and enactive cognition perspective, social interaction "cannot be reduced to so-called 'social information transfer'" (Lindblom, 2020: 10). Rather, social interaction is always relational (Gallagher, 2005; Di Paolo et al., 2010; Fuchs, 2016), where meaning- or sense-making emerges dynamically through "creative co-regulated socially embodied interactions" (Lindblom, 2020: 10; see also Johnson, 2018). Instead of accessing our world through representations, we bodily participate in the generation of meaning, "often engaging in transformational and not merely informational interactions; [we] enact a world" (Di Paolo et al., 2010: 39). My relational-performative esthetic approach to human-robot interaction builds on the embodied, enactive approach, aligned with a performative understanding of how agency is relationally enacted, to develop a deeper understanding of how meaning is bodily negotiated in human-robot encounters.

Much of our embodied, social meaning-making process involves movement and, in particular, movement qualities, allowing us to rhythmically coordinate with others through interaction (Di Paolo et al., 2010) and bodily resonate with affective qualities or environmental affordances (Fuchs and Koch, 2014). Looking at emotions "as embodied responses to meaningful situations" (Fuchs, 2016: 1), Fuchs and Koch understand motion and emotion as "intrinsically connected: one is *moved by movement* (perception; impression; affection) and *moved to move* (action; expression; e-motion)" (2014: 1). A number of researchers have thus explored the expressive potential of motion design beyond imitating human movement and, instead, focusing on how it can affect our interpretation of abstract, non-humanlike robotic artifacts. Levillain and Zibetti have investigated how non-humanlike "behavioral objects" open up possibilities for intuitive connection based on simple, evocative movement patterns (2017). Using the CoBot platform, Knight and Simmons have studied how expressive motion allows for a robot's movements to be interpreted as simple mental states, e.g., happy vs. sad (2014). Jochum et al. discuss theatrical performance practices and entertainment robots, showing that strategies adopted from traditional puppetry can inform creative solutions for robot motion design (2017)[4]. LaViers et al. (2018) have explored tools and techniques from choreography and somatics that can inform the development of expressive robotic systems.

Robot design practices that place movement and its potential for social meaning-making at the center of the design process, from the very beginning, are much rarer. Drawing on techniques from abstract character animation, Hoffman and Ju argue that a "robot's motion can clue users into what actions and interactions are possible," thus playing a significant, yet still "widely under-recognized" (2014: 95) role in human-robot interaction. Dominated by pragmatic and visual approaches, social robot designs, if at all, commonly only integrate movement qualities later in the process, once mechanical and visual development are completed (Hoffman and Ju, 2014). In a motion-centric approach, in contrast, the robot's design is shaped by the communicative potential of movement, unfolding in an ongoing conversation with pragmatic and appearance-related issues (Hoffman and Ju, 2014). In fact, it would be difficult to imagine how a design process oriented toward the quality of movements could not take on an iterative, integrated approach, given that a robot's movement potential relies on its mechanical workings and its perceived effect cannot be separated from its visual presence.

An important example demonstrating this motion-centric approach is Shimon, an interactive robotic marimba player (Hoffman and Weinberg, 2011), featuring a socially expressive and communicative head and four arms that move along a shared rail. Bringing together mechanical looks and gestural movement, the head supports the robot's interaction and improvisation with its human band members (Hoffman and Ju, 2014). Importantly, Hoffman and Ju point out that a motion-centric approach that invests in carefully designed movement qualities to develop a robot's "complexity and sophistication" (2014: 93) can lead to more abstract, geometric designs that afford more feasible and rapid prototyping and testing than humanoid designs. Within this context, Sirkin et al. (2016) have developed a design approach, where movement does not drive new robot designs but rather turns existing objects into communicative social artifacts. Studying "objects *in motion* because interactivity implies sociability" (Sirkin et al., 2016: 95; see also Yang et al., 2015), they have developed a series of expressive robotic artifacts that expand everyday objects, including a mechanical ottoman, emotive dresser drawers, and a roving trash barrel. Aiming to bestow the artifacts with expressive personalities, Sirkin et al. involved practitioners from dance, improvisational theater, and stage theater to operate the objects employing Wizard of Oz techniques in improvisational experiments (2016).

Aesthetics, where referred to in the approaches above, is still only considered with respect to a robot's physical form. In contrast, Popat and Palmer (2005) identify aesthetics as the common ground from which genuinely creative dialogues between performers and technologists can arise and offer an insightful account for embodied knowledge exchange between a dancer and roboticists, mediated by a six-legged robot prototype. Recent creative work in soft robotics has opened up the design space for social robots by offering provocative modes of inquiry into their appearance, movement, and interaction potential (Boer and Bewley, 2018; Jørgensen, 2019). Embracing "the robot as a quasi-other," Boer and Bewley explore alternative ways for human-robot communication through the performative potential of abstract soft robots, based on kinetic expression (2018). Jørgensen has proposed an extensive framework for aesthetics of soft robotics that develops a dialogue between artistic practices and material, ecological thinking to explore the performative potentials and sociomaterial consequences of rendering a robot soft (2019). Both esthetic approaches focus on the interplay between the unique material affordances of soft robots and its expressive movement qualities, e.g., through softness (Jørgensen, 2019) and elasticity (Boer and Bewley, 2018). In contrast to this foregrounding of material performativity, employing movement as a medium to evoke a character or personality (e.g., see Sirkin et al., 2016; Knight and Simmons, 2014; Hoffman and Ju, 2014) suggests that it is the expression of a given character's qualities that shapes the robots' social potential.

Agential enactment and its social effects play an important discursive role in science and technology studies (see Suchman, 2007a; Alač, 2015; Jones, 2018) and cognitive anthropology (see Malafouris, 2013) and gain influence in human-computer interaction research (see Wright, 2011; Hylving, 2017; Frauenberger, 2019). This article argues that the transformative potential of interaction dynamics opens up rich opportunities for how we relate to robots and brings with it new pathways and challenges for how we approach human-robot interaction design. According to Kroos et al. (2012), the question of agency within the context of robots "seems to conjure the 'Ghost in the Machine' once again" (2012: 401), as if it could be given to a machine and, equally, be taken away and transferred to a different machine. Realizing the robotic installation, *the Articulated Head*, the authors found that, instead, "agency cannot be instilled; it needs to be evoked" (2012: 401). To avoid pre-scripted behaviors, Kroos et al. developed an attention model, which plays a central role in a tightly coupled perception-action control system (2014). Following the sounds in the robot's surrounds and tracking visitors' faces, the installation's resulting attentive behaviors are sometimes reminiscent of Edward Ihnatowicz's pioneering cybernetic sculpture *the Senster* (1970; see Zivanovic, 2019). In the remainder of this article, I will explore how movement qualities can scaffold a robot's ability to actively participate in the dynamic meaning-process of an encounter.

[4]Jochum et al. state that "[w]here classical engineering favors precision, artists are trained to look for creative solutions by exploring ambiguity and uncertainty" and "transforming design and technological constraints into advantages" (2017: 374).

FIGURE 1 | MML *Cube Performer #1*, robotic prototype (composite), Games and Performing Arts Festival, United Kingdom, 2018.

DIFFERENCE IN RELATION: MACHINE MOVEMENT LAB

My collaborative *Machine Movement Lab* (MML) project (**Figure 1**) develops an embodied methodology for designing abstract social artifacts to investigate the aesthetics of meaning-making in human-robot interactions by looking at difference in relation. To illuminate some of the core ideas that motivated our methodological development as part of MML, I would like to return to the question of how a robot becomes a social agent. One could argue that whether or not a robot's social agency is given (e.g., by the designer) is inconsequent and, instead, what matters is that it is perceived as a social agent by human interactors. After all, I also said earlier that, from a performative view, what we perceive to be agents is an effect of agential enactment between humans and nonhumans. So why does it matter what or who gives rise to a robot's sociality—do not both approaches produce the same effect and, accordingly, the same possible relationships we can have with robots? I argue that it *literally* matters how we approach the design of social agents, beginning with how we imagine our relationships with them[5].

By understanding social agency as an attribute, it follows that these social qualities need to be defined in ways that allow them to be represented as part of the design of social agents, whether in the form of physical features or programmable capabilities. This requirement quickly connects us back to Mindell's argument that it is the designer's beliefs and intentions that shape a robot's capacities and, consequently, the relationships it brings about (2015). While this is the case with any designed product, the argument gains more significance within the context of artificial social agents, fabricated to tightly integrate into our societal fabric. Beliefs and intentions do not only manifest in marketable, communication-friendly features but also material boundaries in terms of what they include and exclude and, more importantly, *whose* agencies they affirm, extend, omit, or inhibit.[6] Other relevant potential dividing lines that our beliefs manifest through practice relate to how we differentiate between human/nonhuman, mind/body, subject/object, as well as information/matter. Hence, one major assumption shaping our interactions and how we imagine them is whether we believe that these dualisms and the hierarchies they impose are the result of an inherent difference between them or whether they are constructs, enacted and reaffirmed as part of a history of epistemological and ontological practices.

In a performative view, "[a]gency is not an attribute but the ongoing reconfigurings of the world" (Barad, 2003: 818) that our discourses and practices are an inextricable part of (as is matter itself) and it is these ongoing intra-actions that differentially enact boundaries, properties, and meanings (Barad, 2003). Designers and engineers find themselves in the midst of a dynamic meshwork of configurings, and it is impossible to avoid boundary-making or material manifestations of our assumptions. Instead, the goal of my relational-performative design approach is for capacities and boundaries to be negotiable in the encounter, that is, to "give space" to the unfolding of a robot's social capacities and relationships (see Mindell, 2015) in the interactional dynamics instead of pre-shaping them. A relational-performative process, as developed in MML, thus shifts the design focus from designing an "agent" to exploring human-machine couplings (Alač, 2011) and probing into the dynamics through which social agency can emerge in a particular situation. Looking at how an artifact or machine becomes an agent from within the dynamics of the encounter, I argue, challenges rigid subject-object boundaries and renders them more elastic (explored further in the following sections). Aesthetics here does not serve to make the strange look more familiar but is about *rendering differences relational.* The following provides an account of performative meaning-making as it unfolds in our practice, with the esthetic goal to create a rich playground for investigating difference in relation at work by embracing and playfully exploiting the differences between human and machine.

Machine Movement Lab

Starting in 2015, MML brings together creative, embodied practices with robotics and machine learning, grounded in an enactive, performative framework. The project's main objective is to open up alternative pathways to social robot design by investigating the relational, generative potential of movement qualities for meaningful encounters with abstract, social artifacts.

[5]This argument not only draws on my own collaborative practice but also ethnographic studies of interactions in social robotics laboratories that demonstrate the importance of situational dynamics and the role they play in human involvement in a robot achieving social agency (Alač 2011; Alač, 2015; see also Suchman, 2007a).

[6]My brief argument here draws on a much deeper and wider historical and political discourse, e.g., see Suchman, 2007b; Suchman, 2007a; Suchman, 2011; Haraway, 1989; Haraway, 2003; Barad, 2007; Barad, 2003; Hayles, 1999; Latour, 1993; Penny, 2017; Gemeinboeck, 2019, to just name a few.

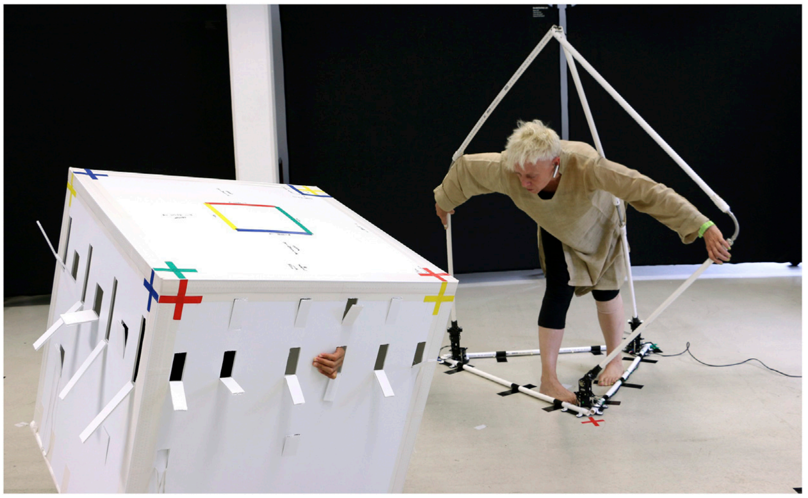

FIGURE 2 | PBM performer-cube and performer-tetrahedron entanglements, with T. de Quincey (right).

The question that guided our methodological development was how can a robot with its unique "machinic" differences become relational and participate in social encounters without tightly orchestrated predefined tasks that would prescribe the social scenario? Movement was identified very early on as being key to transforming the social potential of abstract artifacts (see Levillain and Zibetti, 2017). Instead of looking at movement as a medium for "accurately expressing the robot's purpose, intent, state, mood, personality, attention, responsiveness, intelligence, and capabilities" (Hoffman and Ju 2014: 91), however, MML focuses on the potential of its "distinctive spatial, temporal, and energic qualities" (Sheets-Johnstone, 2012: 49)—qualitative dynamics that cannot only be observed but also kinaesthetically and empathically felt (Sheets-Johnstone, 2012; Despret, 2013; Fuchs and Koch, 2014; Koch, 2014; Gemeinboeck and Saunders, 2018).

The proposition is that the effective, sociocultural dimensions embedded in our movement qualities can serve to bootstrap the robots's learning to situate it in "the social and cultural scaffolds that human embodied beings are situated within" (Lindblom, 2020: 4). The latter are, according to Lindblom, "the driving force for the emergence of our embodied social understanding" (2020: 4). Importantly, the robot's learning also needs to be grounded in its own unique, machinelike embodiment, and the human movement qualities require transformation that responds to the differences of this other embodiment. To investigate this potential, we developed an embodied mapping approach, *Performative Body Mapping* (PBM), which harnesses the expertise of dancers to, essentially, "train" a robot to develop sensibilities for human movement qualities (in the form of learned biases and constraints) without simply reperforming human movements. The goal is not to train the robot as if it was a human dancer; rather, we aim for unscripted, embodied meaning-making encounters with an improvising robotic artifact that has learned a few tricks from a human dancer. But "learning tricks" from a human dancer is a challenge for a simple object without legs, arms, a spine, or head. In fact, we did not know how the object would look like at the start of the process, as we wanted to begin with the movement potential itself, rather than a given shape that has to learn to move.

The first PBM research stage (2015–2018) began with a series of experiments that involved dancers becoming entangled with a wide range of materials to kinaesthetically feel and extend into other nonhuman forms and their material affordances. We then selected two simple geometric shapes, previously inhabited by performers to study the transformative potential of movement qualities, to take on the role of "costumes" that stand in for the real-size shape of a becoming-robot (**Figure 2**).[7] Combining the ideas behind theatrical costumes (Suschke, 2003)[8] and demonstration learning in HRI (Billard et al., 2008), the PBM costume enables dancers to "step into" and inhabit this other nonhuman embodiment to 1) corporeally experience this strange morphology and learn to kinaesthetically extend into and move *with* it, and 2) bypass the correspondence problem (Dautenhahn et al., 2003).[9] This is significant because the PBM costume allows 1) delegating much of the difficult morphological mapping to the movement expert and 2) the robot prototype to learn from the

[7]The costumes were built with lightweight fluted plastic or plywood panels and plastic tubes, see **Figure 2**. A detailed account of this early form-finding stage, selection criteria and movement experiments can be found in (Gemeinboeck and Saunders, 2017).

[8]Theater and performance have a history using costumes to "transform" performers' performance. For example, for his 1993 production of *Tristan and Isolde*, Heiner Mueller asked Yohji Yamamoto to design costumes for the singers "that would impede on the movement they are used to" (Suschke 2003: 205). Rather than interfering with the dancer's movement, however, we are looking for a productive intermeshing (see *Designing with Bodying-Thinging*).

[9]Often discussed within the context of demonstration learning in HRI, the correspondence problem refers to the challenge of mapping between two very different embodiments (Dautenhahn et al., 2003).

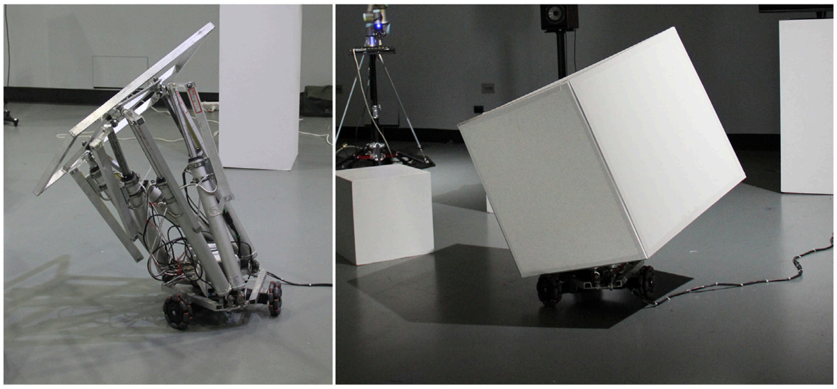

FIGURE 3 | PBM *Cube Performer #1,* robotic prototype (right), and its mechanical frame (left), Sydney 2017.

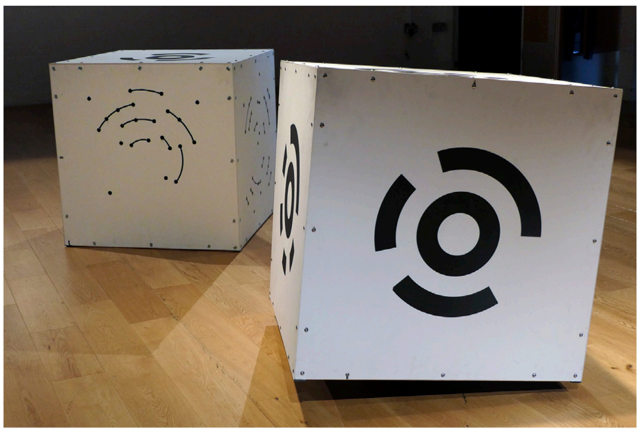

FIGURE 4 | PBM cube costume with *Cube Performer #1,* robotic prototype (right), Games and Performing Arts Festival, United Kingdom, 2018.

motion capture data as if it was trained by another robot performer with the same physical shape. The first stage (PBM) focused on the transformative potential of movement qualities and intra-bodily resonances (see *Bodying-Thinging, Designing with Bodying-Thinging*), while the second, current stage (Relational Body Mapping, or RBM) involves the robot's unique sensorium to explore how movement qualities transform the relational space between different agents, including artifacts, human performers, and the surrounds (see *Dancing with the Nonhuman*).

PBM aims to tap into our bodies' tactile-kinaesthetic capabilities to develop and recognize "the synergies of meaningful movement" (see Sheets-Johnstone, 2010) to exploit one of the most interesting characteristics of robots, from an embodied meaning-making perspective that we can bodily resonate, kinaesthetically extend into, and relationally make meaning with their spatial, embodied dynamics and the relations they spawn. Working with choreography, PBM allows us to create a library of qualitative movement dynamics with dancers' "tactile-kinaesthetic bodies" Sheets-Johnstone, 2010) from within the different material-relational perspective of the robotic embodiment. This bodily inventive process, in Noland's words, "entails nothing less than the performative construction" of the dancer's body (2009: 1). We deliberately do not work with narratives or emotional states but, instead, performers often use mental images of nonhuman dynamics, e.g., reimagining their body as a distributed nervous network,[10] to guide the reconfiguring of their bodies and finding of new movement patterns.

So far, we realized one of the costume bodies as two robotic prototypes, *Cube Performer #1* (**Figure 3**) and *Cube Performer #2*) as part of our iterative design process[11] (I will look at how we arrived at this particular, familiar shape in more detail in *Designing with Bodying-Thinging*). The Cube Performer has exactly the same dimensions as the cube costume (75 × 75 × 75 cm; see **Figure 4**) because we consider the scale of the artifact's shape to be an important part of its material embodiment and the spatial relations it can bring about, and, with regards to PBM, it matters that the two align. We derived the movement requirements for their mechanical design from an analysis of over 10 hours of motion capture recordings to determine the required degrees of velocity and acceleration, as well as ranges of movements—vertically, horizontally, and rotationally (Gemeinboeck and Saunders, 2018). Being essentially plain cube objects, we conceived their mechanical structure to permit changing the outer "skin" of the cube to allow them,

[10]I refer here to the work of our collaborator, choreographer Tess De Quincey, and her mental image of the "nervous body," developed as part of her *BodyWeather* practice (see https://dequinceyco.net, accessed on 17 June 2020). Sourced from a video recording of a PBM movement study, 26 March 2016 (unpublished). For more discussion of mental imagery in dance see also Foster, 2000.

[11]We took the opportunity of turning one of our iterative prototyping stages into building a complete, second prototype to have two robotic artifacts to work with, e.g., for studying the performative potential of machine-machine couplings or incorporating them in performance settings with human performers (see *Dancing with the Nonhuman*). Descriptions of our first design of a robotic artifact, the *Cube Performer*, its mechanical design and early machine learning stages can be found in (Gemeinboeck and Saunders, 2017; Gemeinboeck and Saunders, 2018; Saunders and Gemeinboeck, 2018).

like a performer, to integrate into different environments and contexts of encounter (see *Designing with Bodying-Thinging*). It is worth pointing out that the purpose of these prototypes is primarily that of a *materialized, situated research proposition* that allows us to 1) inquire into the potential of relational-performative aesthetics for human-robot encounters and the possible human-machine couplings they entail and 2) develop human-nonhuman performance scenarios to engage publics in important questions about human-robot relationships (see *Dancing with the Nonhuman*).

Humanlike or Machinelike

Designing with a focus on human-machine couplings, I recognize that the polarization of humanlike vs. machinelike is not helpful and in the following attempt to outline in what ways I understand and use these terms both in our MML process and in this article. In my conversations with choreographers and dancers, I often refer to terms such as humanlike or machinelike to delineate between human body configurations or (habitual) human movement patterns and mechanical configurations or the precise steadiness of robot motion. But, over the course of our PBM movement studies, "machinelike" would also come to denote our "destination," that is, no longer standing in for typical machinic motion but for movement characteristics that emerged in conjunction with the robot's spatial-material affordances, activated by a performer-in-costume. With respect to robot design, I use "humanlike" to refer to a designer's deliberate intent to mimic the human as well as to identify the moments in our process in which we slip into ascribing humanlike qualities to movements performed by the performer-cube entanglement. As our objective is to give space to emergent qualities and unexpected meanings unfolding in the encounter (see also Levillain and Zibetti, 2017), we seek to avoid deliberate inscriptions of specific human meanings or intents as part of the design process. Possible "machinelike" inscriptions that, within the context of our PBM process, are specific to our interpretations of the machine embodiment and its performative potential do not seem to confine the space of possible enactments in the encounter. On the contrary, the blank canvas offered by the plain, regular shape when juxtaposed with a rich variety of movement qualities, seems to open up a wide space for potential "spatial transformations that can be interpreted as actions" (Levillain and Zibetti, 2017: 5) as part of the meaning-making process in the encounter. The results of our participatory studies support this observation, with participants reporting, on average, that they perceived the robot as machinelike yet also evocative, affective, and spontaneous.[12]

While aiming for giving ample space to the enactment of potential meanings in our design process, it is important to note that it is not our intention to avoid anthropomorphic interpretations as part of interactors' embodied meaning-making process (Levillain and Zibetti, 2017; Airenti, 2015; Hoffman and Ju, 2014; Gemeinboeck and Saunders, 2018). Our aim is for the robot's performed movement qualities to serve as an empathic-affective scaffold (see Koch, 2014) for interpreting and making meaning while preserving the robot's unique otherness. My concept of *bodying-thinging* (*Bodying-Thinging*) directly speaks to the potential effects of this juxtaposition. Hence, rather than aiming to control or channel participants' interpretations, my relational-performative approach seeks to emphasize the significance of allowing the space for sociality and meaning to be enacted in the encounter, which naturally includes unexpected interpretations and responses (Levillain and Zibetti, 2017).

BODYING-THINGING

Returning to the question posed at the beginning of this article, this section explores how an *abstract robotic artifact* becomes an evocative participant in social encounters. Levillain and Zibetti (2017) asked a very similar question, looking at behavioral objects and how they trigger human attributions of animacy. While cognitive psychology takes its viewpoint from the human "side" of the encounter, does positioning oneself "in the middle" offer alternative relations? Notwithstanding that our (human) perception, social expectation, and interpretation (Levillain and Zibetti, 2017) play an important role in our meaning-making processes, in Barad's agential realist account, "meaning making is not a human-based practice, but rather a result of specific material reconfigurings of the world" (2007: 465). A performative perspective on how subjects and object are enacted, in tandem with embodied meaning-making, allows us to not only revisit this divide but to also look at the esthetic, transformational potential of (what we know as) subjects and objects encountering and reconfiguring each other.

The Cube Performer, for instance, brings together the thingness of a "thing" and the dynamics, resonance and affects that "bodies" commonly engender, which seems to suspend the artifact in a position between the two—a thing-body or a body-thing. Looked at closer, this is not a fixed position between the two but rather an ongoing differing—a *bodying-thinging*: a thing becoming more body and the "more body" becoming "more thing" again, and so on. But "bodying" here is not what a body does nor a "thing becoming body." "Always triggered relationally" (2014: 42), according to Manning and Massumi, it is movement that "bodies-forth" (2014: 39). Rather than a body (or a thing), it is movement in its dynamic differing that is "bodying." And, neither is "thinging" done by what an object represents. In his seminal text on "the Thing," Heidegger states, "[i]f we let the thing be present in its thinging from out of the worlding world, then we are thinking of the thing as thing" (1971: 178), untied from an object's utility. As (human) interactors bodily empathize with the artifact becoming more than what the

[12]We conducted two participatory studies: the first three-day study involved 48 participants and took place as part of the exhibition *RePair* at the *Big Anxiety Festival*, Sydney, November 2017; the more detailed follow-up study, in February 2019, involved ten participants as part of a two-day open lab, both situated in the same performance space at the UNSW Art and Design campus. Details on study design and discussion of results can be found in (Gemeinboeck and Saunders, 2018; Gemeinboeck and Saunders, 2019). In this article, I take an anecdotal approach to reporting participants' feedback to complement my conceptual/theoretical argument with material-experiential accounts.

object represents, they are *bodying-thinging* in resonance with the *bodying-thinging* of the robotic artifact. Despret, writing about how we seek to understand animal behavior, describes this transformative bodily reading and communicating as "'undo[ing] and redo[ing]' each other" (Despret, 2013: 61). The boundary reconfiguring, that is, *bodying-thinging* thus allows (human) interactors to corporeally resonate and respond to a dynamically moving artifact, whose embodiment and behavior are very different from their own. Intelligibility here is not confined to matters of intellection but "rather more generally may entail differential responsiveness to what matters" (Barad, 2007: 470). In Despret's concept of "embodied empathy" (2013), this ongoing attunement is reciprocal but not symmetrical and always only partial. Hence, *bodying-thinging* is not about turning objects into subjects or the other way around but about bodily making meanings across the subject-object divide and rendering elastic fixed boundaries in the process.

Bodying-thinging, I propose, is a form of *entangling*—how subjects and objects entangle and are transformed in the process of human-robot encounters. Entanglements, in Barad's words, "are not unities. They do not erase differences; on the contrary, entanglings entail differentiatings, differentiatings entail entanglings" (2014: 176). Writing about machine performance, Dimitrova identifies a "constitutive connectivity [that] allows bodies to become dissipative structures," an empathic "being toward" that allows us to "peer into regions that were previously unintelligible" (2017: 175). Yet, this potential for connectivity is not restricted to organic bodies (see Dimitrova, 2017) but is also how bodies and things entangle and subject-object boundaries become porous, opening up mutual intelligibilities.[13] In my relational-performative view, machines are no longer positioned outside the social and do not need to be given sociality with, for example, a humanlike veneer. As we will see in the following section, *designing with bodying-thinging* is the playground of a relational-performative aesthetics, mobilizing and embodying our attention to causal enactments and their "ongoing differentiating intelligibility and materialization" (Barad, 2003: 824) that we participate in, designers and participants alike. Dance and choreography are natural allies for bodily inquiring into human-nonhuman encounters and how they *reconfigure relations*, the kinds of which that induce forms of *bodying-thinging.* Dancers are extremely attuned to their body's ongoing reconfigurations in relation to space, other bodies and things, and more so, can be highly skilled to tune into and reconfigure other bodies and things. This relationality, affectively *being toward* through movement, is described by Leach and deLahunta, 2017 as "an extension of feeling, knowing, and sensing into the world *with*, and of, other bodies" (2017: 464). In the following, I will take a closer look at PBM and how the dancer bodily and kinaesthetically tunes into the otherness of a robot's embodiment through the PBM costume.

The esthetic, performative differing of *bodying-thinging* not only frames the process of how subject-object boundaries are continually enacted and transformed in an ongoing "undoing and redoing" each other, but in PBM also materially manifests in the performative mappings. PBM harnesses dancers' ability "to become virtuosos of coping," which means to become, in Noland's words, "experts at adapting their own sensorimotor instrument to the situation at hand" (2009: 1). According to Noland, technology in choreographic contexts serves to establish environments and situated demands that challenge dancers "to discover the ways human bodies produce themselves (how they refine their capacities and thus assume new shapes)" in relation to these demands (2009: 1).[14] This relational bodily reconfiguration perfectly encapsulates the *bodying-thinging* that goes on in the PBM performer-cube entanglement. A dancer, who has inhabited the cube costume[15] for over 30 h, described her coping response to the challenge posed by the costume as her "body extending into the cube." To "give weight to the costume," for example, she needs to assume different shapes that afford her "to transfer tension by pressing against [the costume's] surfaces"[16] (**Figure 5**). Coping here is about skillfully intra-acting with the environment and its relational affordances, rather than controlling what might else be seen as a passive "container." By "extending into the cube," the dancer does not impose her body onto the artifact but rather "becomes body-thing" with the cube. Importantly, as she becomes a virtuoso of this intra-active coping, her proprioception also transforms to afford her to kinaesthetically sense her body-cube entanglement and its movement and position in space.[17] It is this bodily-kinaesthetic probing and puzzle-solving (see Noland, 2009) and how it performatively reenacts bodies and things as relations of *bodying-thinging* that is at the heart of my relational-performative aesthetics.

Bodying-Thinging in PBM is not a simple transaction like the human dancer "bodying" the machine or the machine "thinging" the human dancer. Bodying or "bodying-forth" denotes to the relational meanings produced by the machine's differing through movement dynamics—a being toward that we usually connect with the lifelike or animated. Importantly, movement here is not only about couplings between bodies and the environment but also brings with it cultural and historical couplings (see Gamble et al., 2019). By "thinging," the machine brings forth its "thingness," an

[13]Suchman reminds us that mutualities are not necessarily symmetries, suggesting "that persons and artifacts do not constitute each other *in the same way*" (2007: 269). Contrasting representational approaches to human-robot interaction design, this relational-performative approach embraces the asymmetries between persons and artifacts.

[14]Discussing her notion of coping, Noland talks about co-construction, where dances and bodies are "performatively produced in dialogue with external devices" (2009: 3).

[15]The cube costumes consist of a lightweight aluminum frame, 75 × 75 × 75cm, with either five plywood or three plywood and two Plexiglas faces (see **Figure 5**).

[16]Based on an unpublished interview with Audrey Rochette on 3 July 2019, University of Applied Arts Vienna.

[17]Dancers who inhabited the PBM costume (nine in total) have stated that their proprioceptive sense increasingly extends to the performer-cube entanglement (based on conversations with collaborating performers captured in video recordings of movement studies, on 31 January 2017, 15 March 2018, 24 January 2019, 3 July 2019 (unpublished).

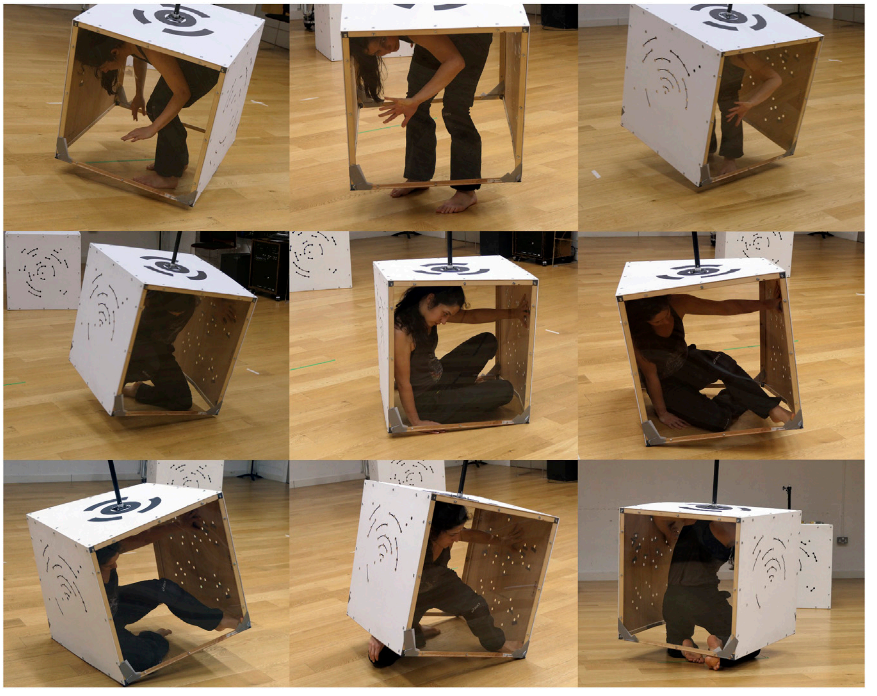

FIGURE 5 | PBM performer-cube entanglement in sequence, with A. Rochette.

otherness unique to the machine and the relations it constitutes and is constituted by, commonly in conflict with notions of the animated. Yet, according to Heidegger, the "thinging of the thing" also brings forth a "nearing," a nearness being "at work in bringing near" (1971: 175). While entangled, based on our observations of how performers, choreographers, and participants make sense of the encounter, *bodying-thinging* has the effect of rendering the artifact in motion *at once stranger and more familiar*. For example, in one of our PBM experiments, guided by the image of breath and how it changes according to different bodily states, the performer-inside-costume balanced with the cube on one corner, while raising the diagonal corner using varying qualities of velocity, rhythm, projection, and weight. Naturally, neither the costume cube nor the robotic cube is perceived as "breathing" as a result. However, the dynamic motion patterns that they perform arising from the dynamic qualities brought forth by this image render both the costume and the robot's machinelike performance of it stranger and more familiar at the same time. The effect of this affective juxtaposition has been expressed by one of our study participants[18] as "I like its non-humanness . . . there is a companionability to it. Wow." Another talked about approaching it "as a subject but then it flips around and does something else." Participants also described their intra-bodily resonances in ways that parallel their relationship with nonhuman animals, saying, "I responded to it like another species and increasingly so" or "it comes across as playful . . . like a wild animal."

Writing about our encounters with companion species, Haraway poignantly observes that embodied communication "is more like a dance than a word: the flow of entangled, meaningful bodies in time—whether jerky and nervous or flaming and flowing, whether both partners move in harmony or are painfully out of synch or something else altogether—is communication about relationship, the relationship itself, and the means of reshaping relationship and so its enacters" (Haraway, 2008: 26). We *body-thing with* the artifact.[19] The resonances felt as one is entangled in this dance are, I argue, not only one-sided projections or attributions that bestow either animatedness or thingness onto an artifact,[20] rather meaning arises with respect to how the artifact actively extends toward us—how it *body-things*—and how this "intra-bodily resonates" (Froese and Fuchs, 2012: 212) with us and we extend toward it in response.

[18]I refer here to our participatory study in 2019, involving ten participants as part of a two-day open lab at a performance space at the UNSW Art and Design campus, discussed in more detail in (Gemeinboeck and Saunders, 2019).

[19]This is not a figure of speech. As our kinaesthetic experiences are grounded in embodiment (Johnson, 2007; Sheets-Johnstone, 2012; Lindblom, 2015), our thoughts and feelings are equally grounded in our bodily interaction with other bodies, things and the environment (see Meier et al., 2012; Fuchs, 2016). They manifest in embodied ways in what Froese and Fuchs have termed "intra-bodily resonance" (Froese and Fuchs, 2012: 212) and express themselves to others, interpreted, in turn, via intra-bodily resonance. *Bodying-thinging* aligns Froese and Fuchs' intra-bodily resonance with Despret's ethological concept of "embodied empathy" (2013).

[20]Based on their cognitive psychology studies, Levillain and Zibetti argue that objects' distinct behavior produces transformations that trigger "the same kind of attributions that would be activated by the motion of a living being" (2017: 13).

Affective and agential effects here arise from the entangling of *bodying-thinging*, rather than individual control or one-sided projection.

DESIGNING WITH BODYING-THINGING

As we shift from a representational view, anchored to distinct entities, built-in agencies, and fixed boundaries to a relational-performative approach, design as a practice becomes part of reconfiguring the world (even if only a very small part of it). Entanglements with the nonhuman not only involve (preformed) objects and machines but matter itself and the different sociomaterial relations it is embedded in. A relational-performative design approach is thus more akin to humbly participating in the "ongoing open process of mattering through which 'mattering' itself acquires meaning and form in the realization of different agential possibilities" (Barad, 2003: 817). Meaning-making here happens as part of a process of embodied, situated material engagement (Malafouris, 2013), where materiality is not a matter of representation but rather of capacity and relationality—what it *does* and how it can *participate in* the wider meaning-making context. This inseparable entwinement of embodied, material engagement, agential enactment, and meaning-making is core to our MML design process. Its embodied attentiveness to the relational in meaning-making also aligns with Dourish's (2001) embodied interaction approach to HCI design that offers a method of attending to the situated, social aspects of meaningful embodied encounters. Embodied, material engagement and relational meaning-making thus not only play key roles when a robot is "ready for relationships" (Turkle, 2005: 288) but are equally core to the design process. This is where the material relation-making begins.

Our human-robot encounter begins when we imagine the robot, experiment with its design, prototype it, and share, evaluate, and make meaning of its *bodying-thinging* and *body-thing* with it. This is how we can *design with* its relational potential and the dynamics it arises from, along the process, rather than encountering the robot for the first time at the end of the design process. In such a performative process, the design brief for a robot is never complete, because the intra-active process of both design and encounter (i.e., human-robot interaction) constitutes and continuously reconfigures capacities for relation-making. In order to give space to the enactment of relations and the making of meaning in the encounter, I propose that the two distinct processes of design and encounter need to be understood as one continuous process—*designing with* the encounter.[21]

Giving Space to Bodying-Thinging

The difference of *designing with* the encounter (rather than *for* the encounter) is how we attend to 1) the agential networks that nonhuman materialities are embedded in, as well as 2) the agencies and meanings that our process inevitably makes manifest in the design, whether deliberate or unwittingly, and 3) how these (1 and 2) intra-act with the meaning-making, later, in the encounter with participants. Every design process necessarily involves decisions that include certain possibilities and exclude others and that eventually manifest in specific material forms and behaviors (see also *Difference in Relation*). Let me briefly introduce some stages of our process and how it was propelled by the transformational potential of relational movement qualities and material affordances.

Our PBM design process began with *unfixing* relations by materially investigating them, rather than focusing on tasks and their potentially already fixed relations. Doing so, our process started with a series of human-nonhuman encounters, with dancers bodily probing into the performative potential of a wide range of material relations. This early stage, which favored movement and relationality over visual characteristics, focused our esthetic approach on investigating the potential of "disjunction of form and movement" (Bianchini and Quinz, 2016). Continuing, we began to bodily probe into the transformational potential of simple geometric shapes in motion, e.g., cylindrical, cuboid, cubic, and tetrahedral forms, made of qualitatively different materials, e.g., stiff, elastic, and springy (**Figure 6**). While materials with a built-in kinetic capacity, once activated by a dancer, made for an interesting and playful process of generating continuously changing objects, their transformational potential was dominated by physical transformation (e.g., folds, twists, and stretches), rather than relational movement in space. Fast-forward through a few more weeks of embodied experimentation and this is how we arrived at the cube[22]—first as costume and later as robotic artifact. A cube presents a highly abstract yet familiar form, which, on its own, is not usually considered to be expressive or having a social presence. Looking at body-space relationships, a cube's regular, symmetrical, and omnidirectional geometry counterposes organic structures (e.g., human) with limbs, two-sided symmetries and the hierarchy of front and back.[23] Most familiar when sitting flat, rooted in place, a dynamically or delicately moving cubic object, suddenly tilting up, gently swaying. or rambunctiously thumping onto the ground, quickly loses its rootedness and, with it, its stability (**Figure 7**). Hence, a mechanical cube, learning from a human dancer, performs the disjuncture of plane, regular appearance and

[21]It may be worth clarifying that my argument for our encounter beginning with the early stages of design does not require specific design techniques, such as PBM or bodystorming. The latter is a technique from experience design and differs from PBM in that it focuses on looking at a (not yet existing) product from a user's perspective, e.g., by simulating the environment of use or by "employing 'actors' and 'props'" to act out possible ways of use (Schleicher et al 2010). While my notion of *designing with* emphasizes embodied meaning-making, it does not refer to designers projecting themselves into the user's position (although this is always a desirable strategy when we design for others). Speaking to the beliefs and intents that we bring to the design process (e.g., by shifting from a representational to a relational approach), my argument is that, from a relational-performative perspective, the embodied, material meaning-making of our design processes already affords us and constitutes a situation of encounter.

[22]We also built a second costume in the form of a tetrahedron and studied and probed into its kinetic capabilities (see **Figure 2**). Built of elastically connected pipes, a serendipitous accident soon turned the simple tetrahedron shape into a 5-jointed, broken tetrahedron This is still a robot in waiting (see Gemeinboeck and Saunders, 2017).

[23]It is this omnidirectional, regular geometry that usually lends specific functionalities to cube shaped robots, e.g. in reconfigurable modular robot design (see Brunete et al., 2017).

FIGURE 6 | PBM material studies with fabric costumes, inhabited by performers.

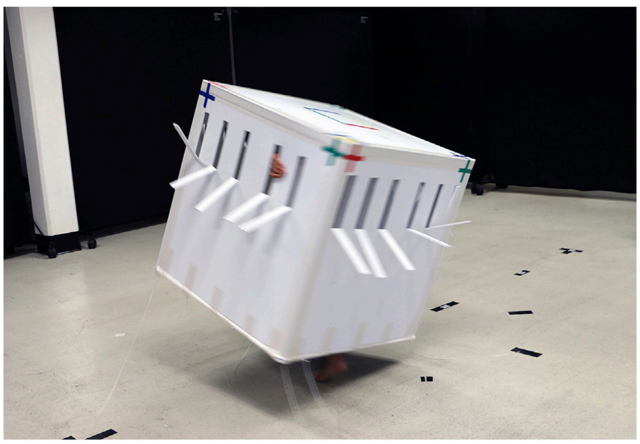

FIGURE 7 | PBM performer-cube entanglement in motion.

intricate, dynamic movement. The thing becomes a body-thing, transformed through the relational dynamics of movement.

The latter could suggest that the dancer inscribes the machine with her human intent as she bodily extends into the costume, whose motion-capture recordings seed the machine learning. Indeed, it is the *bodying-thinging* of the performer-cube entanglement through which the framing of possible human-machine encounters and the potential for relational meaning-making is beginning to take shape, quite literally. Rather than aiming to inscribe the robot with human intent in the form of representational gestures (McNeill, 1992) or narratives, we work with choreographers and dancers to socioculturally situate (see Lindblom and Ziemke, 2003; Lindblom, 2020) the abstract artifact by bootstrapping its learning process based on qualitative movement dynamics. Importantly, these movement dynamics arise from choreographic abstractions (see below) or improvisations in which the dancer entangles with the "other body" of the machine to perform the identity of this other, machinelike "body"; through this entanglement, the performer is tasked with exploring the enabling constraints of the costume rather than anthropomorphizing or imprinting themselves onto the cube. Our motion data then capture the kinetic dynamics of the performer-cube entanglement and comprises granular, discrete movement patterns, derived from short choreographic abstractions, that is, movements that can only be observed "as movement *per se,* for the sake of motion itself" (Aviv, 2017: 4). In the machine learning process, this catalog of dynamic movement qualities serves as aesthetically and socioculturally coded biases and constraints. The robotic artifact learns to compose new movements based on these learned biases and constraints, but, importantly, its learning has also been grounded in its own unique material embodiment. I thus put forward that the Cube Performer's relational potential is shaped by the dynamic movement qualities that the machine performs, situated in the sociocultural, human context of the research team. In linking back to Haraway's statement that communication is more akin to dance than a word (2008), seeding the material-digital process of the robot learning to move with abstract relational patterns that we know how to corporeally "read" or intra-bodily resonate with affords the machine participant to *dance with* its human interactors. Yet, the familiar patterns not only get displaced as they are digitally mediated but also transform in the machine-grounded learning process and the robot's mechanical performance. Movement data here also are *body-things*.

Simon Penny's artwork *Petit Mal* (1989–2005) opens up another esthetic approach to exploring how a machine actively participates in the encounter, showing how its relational potential arises both from its unique machine embodiment and the dynamics of the particular situation it is embedded in. A pioneering example of a machine performer, *Petit Mal*, appears neither humanlike nor animal-like and behaves and relates to its world in ways that are unique to its machine embodiment. Resembling a strange, responsive dicycle, the work's unique behavior results from an eccentric mechanism based around a double pendulum, which brings an unpredictable charming quality to its movements, swaying through the gallery space to "engage visitors in large-scale bodily interaction—a dance," (2016: 57). In his writings, Penny has long been critical of the dualist computationalist separation of software/hardware and information/matter, in favor of a performative view (2017 and 2011). *Petit Mal* embodies this view with hard- and software developed contingent on one another. What is particularly interesting with regards to the machine's unique embodiment and ability to engender affect and relationality is the complexity of its movements resulting from, by comparison, a simple mechanism. Based on the artist's embodied, processual and antirepresentational approach and observations of audiences' bodily responses[24], to me, *Petit Mal* is *bodying-thinging*. I am not sure, however, that the artist would agree with me. In tandem with descriptions of *Petit Mal*'s relationality being enacted as part of interactional dynamics, he frequently positions the work as "an autonomous machine" (Penny, 2011: 85; see also 2000, 2016, and 2017), which suggests an understanding of autonomous agency as a condition for participation rather than the effect of its relational network being cut off (Suchman, 2007a). In contrast to my approach here, Penny's performative ontology of an "aesthetics of behavior" counters notions of entangling and agential enactment in favor of autonomous machines that "make decisions and take actions" (2016: 401).

Narratives of machine autonomy position the artist/designer outside of the ongoing reconfigurings of the world (see Barad, 2003; Stacey and Suchman, 2012) and serve to detach the machine from the designer, its users/participants, and the wider network that the machine and design process are embedded in. In contrast, once we find ourselves inside and part of the ongoing reconfiguring, we are no longer distant or external and can only design *with* the relational dynamics and the contexts they arise from. Suchman talks about the singularity of the interface exploding "into a multiplicity of more and less closely aligned, dynamically configured moments of encounter within sociomaterial configurations, objectified as persons and machines" (Suchman, 2007a: 268). This is the "stuff" that we design *with*.

Opening Up Spaces for Emergence Through Staging

Staging is an important practice for HRI, allowing a robot to be situated in various sociomaterial and cultural settings and frequently used to promote a robot's autonomous agency (see Suchman, 2007). While often overlooked as part of the design process, from a relational-performative perspective, staging is in itself a powerful esthetic intra-action that actively sets and shifts boundaries by "systematically foreground[ing] certain sites, bodies, and agencies while placing others offstage" (Suchman, 2007a: 283). If we think of encounters as intra-actional performances (see Barad, 2003; Barad, 2007), then staging is the making of their performance context, giving space to or inhibiting possibilities for entangling (*bodying-thinging*).

While it can be tempting to exploit our age-old fascination with self-moving machines by staging them as visual spectacles, I have so far approached the staging of the Cube Performer through the aesthetics of the anti-spectacle. This, in my practice, involves nestling the robotic performer(s) into an environment in ways that foreground the unfolding dynamic enactments and how they transform the situation.[25] As MML has so far focused on methodological development rather than performance-making (see *Dancing with the Nonhuman*) our staging considerations mostly involved how the robot visually integrates in existing (gallery) contexts in ways that heighten its relational potential brought forth by its movement qualities. Importantly, this also meant that we present the Cube Performer as a prototype or "research work in progress" rather than a complete artwork, motivated to show the prototype at different stages of the PBM process to gain insights into whether and how audiences/participants "intra-bodily resonate" and engage with the robot in an unscripted encounter. So far, we have staged very simple first-encounter scenarios with the Cube Performer as part of two public exhibitions,[26] e.g., integrating *Cube Performer #1* into the gallery context by staging the prototype as a gallery plinth among a group of other (immobile) plinths (**Figure 8**). In the open-lab study,[27] without an exhibition context, the robot took on a utilitarian identity to blend into the studio/lab context, appearing like a simple wooden box (**Figure 9**). These "humble" stagings suited our iterative prototyping stages and the contexts of encounter, particularly since, to us, staging is about preparing the ground (including the looks of the artifact) for giving space to the possibilities generated by the movement dynamics of the robotic artifact. Integrating the artifact in the environmental context worked so well that, at the opening, two audience members jumped when the apparent plinth, which they placed their glasses on, began to twist toward them (more discussion of audiences' responses can be found in *Discussion*).

Louis-Philippe Demers' *The Tiller Girls* (2010) is an example of a meticulously choreographed stage work that gives ample space to emergent relations and even welcomes unplanned collisions and tumbles. The work brings into conjunction the cultural legacy of the 1930s (human) dance ensemble, named "The Tiller Girls," with a troupe of 32 small machine performers. The robots, deployed as machine performers in *The Tiller Girls,*

[24]Sadly, I have not had the opportunity to encounter Petit Mal myself.

[25]My earlier artwork, *Accomplice* (2012–14), was similarly conceived as a robotic anti-spectacle: embedding four robots into the architectural fabric of the gallery; they are mainly present through the material traces of their workings, and audiences can only catch glimpses once they cracked open the wall as they track their relentless knocking sounds (Gemeinboeck and Saunders, 2016a). Accomplice by Petra Gemeinboeck and Rob Saunders is a machine installation that generates its own performance space over time: https://vimeo.com/101790975 [Accessed on 21 April 2020].

[26]*RePair* at *The Big Anxiety Festival,* Sydney, 2017, and the *Performing Arts* and *Games Festival 2018*, United Kingdom.

[27]UNSW Art and Design, February 2019. Details can be found in (Gemeinboeck and Saunders, 2019).

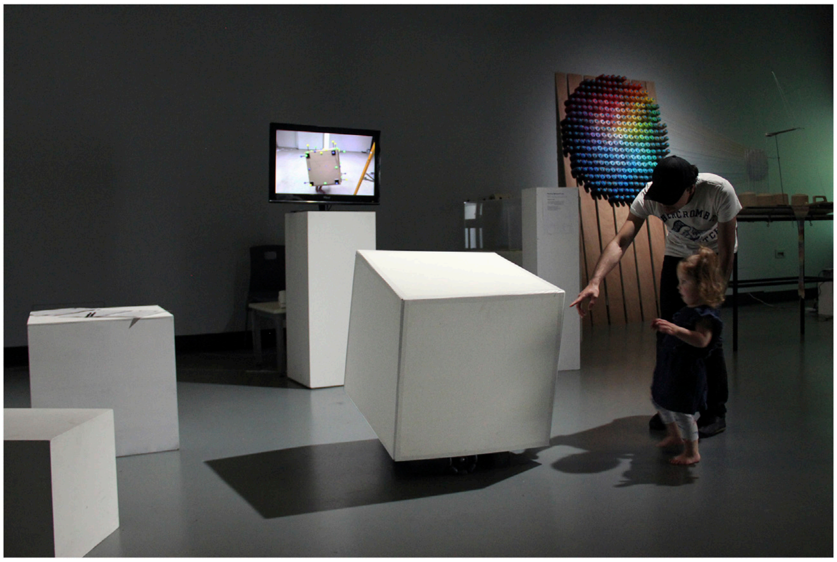

FIGURE 8 | MML *Cube Performer #1*, robotic prototype, at RePair, The Big Anxiety Festival, Sydney, 2017.

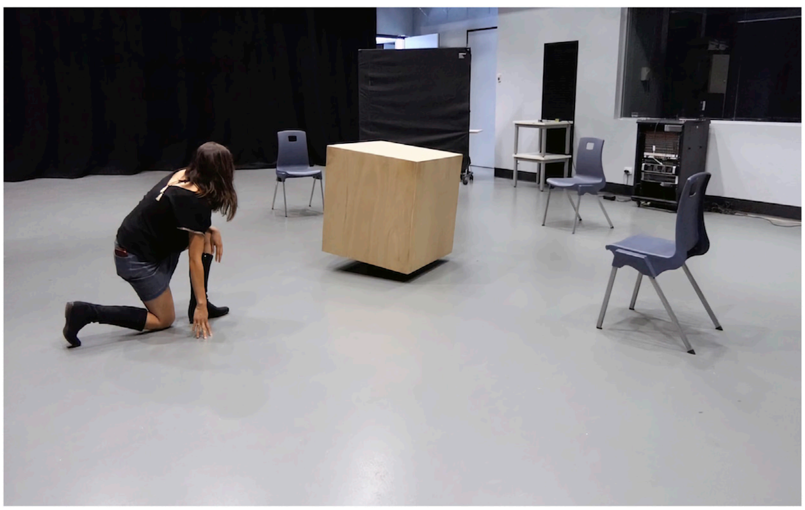

FIGURE 9 | MML Study, participant with *Cube Performer #2*, robotic prototype, Sydney, 2019.

were originally developed by scientists Fumiya Iida, Raja David, and Max Lungarella at the Artificial Intelligence Lab, Zurich, to "study locomotion and gaits derived from simplified morphologies" (Demers, 2016: 281). Demers' dramaturgy utilizes the movements and their "fairly rich" qualities produced by these unusual morphologies to contrast "The Tiller Girls" human yet machinelike performance. Opposing the highly synchronized lines of the human ensemble, Demers' performance unfolds through a dramatic staging of simple machines rhythmically hopping and occasionally falling as part of a "structured chaotic 'improvisation'" (Demers, 2016: 288) (**Figure 10**). Similar to the aesthetics of the aforementioned "disjunction of form and movement," this choreography puts to work the performers' abstract, simple shape to produce a surprising range of unique movement characteristics (Demers, 2016) that give the troupe a dynamic, unpredictable, and whimsical quality. Like Penny, Demers exploits emergent movements of a simple mechanical structure, here an inverted pendulum, to aesthetically explore notions of "intra-bodily resonance" (Froese and Fuchs, 2012: 212). Performance techniques here are employed to investigate how objects transcend their objectness (see Jochum and Goldberg, 2016) by aesthetically exploiting their physical capacities while opening up notions of *bodying-thinging* to historical enactments that shape

FIGURE 10 | *The Tiller Girls* by Louis-Philippe Demers, V2 Rotterdam, NL, 2010.

how we understand bodies. With it, *The Tiller Girls* dynamically enacts a dramaturgy that shows how staging can open up spaces for emergence to shift and unmake boundaries.

Looking at agency and how it constitutes the machine as performer, all three approaches, Demers's *The Tiller Girls*, Penny's *Petit Mal*, and our *Cube Performers #1 and #2*, favor movement over morphology.[28] Yet, we have arrived at three quite different perspectives on how a machine artifact becomes more than an artifact based on its dynamic movement qualities. In Demers's view, *agency is attributed* to the machine performer by the audiences' perception (2016). Interestingly, both the artist and the machine performer have to do work to align the performer's multiple bodies with its behavior: the machine performer has to align its behaviors with its body and the artist then has to align its behavior with its "given social embodiment" (Demers, 2016: 303). This work, I suggest, serves to modulate the audiences' perception through the quality of the alignment, e.g., diminishing the performer's presence "[w]hen the body feels animated, mechanical" (Demers, 2016: 303). In Penny's view, *agency is given* to the artifact through the design/coding of its "sophisticated behavior" that then allows the agent to "take actions" (2016: 401), albeit in *Petit Mal*'s case it is both the artist's coded behavior and the instable mechanism, which generates the movement qualities, that bestow it with agency (Penny, 2000). And, in my own view, agency is neither the artifact's nor the audiences' to give but, instead, *agency is enacted* in the interactional encounter, which the artifact participates in through its dynamic movement qualities. All three views put forward that it is an artifact's surprising range of unique movement dynamics that amplifies its relational potential in the encounter (see also Levillain and Zibetti, 2017). In both, Demers's and Penny's works, this surprising range and unique quality arise from the machines' dynamic morphological computation, while our Cube Performer enacts these relational dynamics based on PBM's intermeshing of human and machine's very different ways of being.

DANCING WITH THE NONHUMAN

In this section, I briefly introduce my current project, Dancing with the Nonhuman, which sits under the umbrella of the MML project but has its own distinct scope and objectives.[29] Performance practices have a long history of developing new kinds of agential relations, where the making of the work relies as much on nonhuman "things" as on humans, or where agency emerges across human and nonhuman domains based on an intimate collaboration between the two (Gemeinboeck and Saunders, 2016a; Eckersall et al., 2017).[30] Dancing with the Nonhuman investigates the potential of performance-making as a research practice to embed our Cube Performers and their machine learning in the sociocultural and sociomaterial milieu of a dance studio. One major goal is to create a public performance work that involves nonhuman (machine) performers and human performers and is open to audience participation. Our process is thus concerned with how the

[28]It is important to note that favoring behavior over form is by no means unique to these three works. Already in 1997, Kac (1997) identified artists "giving precedence to behavior over form" as a principle of robotic art. Penny also stresses this point in (2017).

[29]Dancing with the Nonhuman is a three-year project and, at the time of writing, is nearing the end of its first year.

[30]Other recent examples of collaborations between performance and robotics that develop performance-led methodologies include St-Onge et al. (2019) exploration of robotic swarms and how motion-based expressivity can convey information, and Jochum et al. (2016) employing applied theater as a platform for studying human-robot interaction (see also Relevant Positions and Practices). The performance project *Grace State Machines* (2007) by Bill Vorn, Emma Howes and Jonathan Villeneuve explores questions of kinaesthesis and perception in a dialogue between machine performers and a dancer: https://billvorn.concordia.ca/robography/GraceState.html (accessed on 12 October 2020).

Cube Performer becomes a creative machine performer (see Maher et al., 2008) to facilitate co-improvization with dancers and audiences. The approach situates our robot design in the development of a performance-making practice, rather than bringing performance techniques to the development of a robot design practice. The former permits us to explore meaning-making and specific configurations of *bodying-thinging* from the perspective of the encounter as performance event, fusing the esthetic with “the social, political, and ethical” (Fischer-Lichte, 2008: 172).

To situate the machine performer within the continuously evolving performance context, our approach builds on PBM’s embodied mapping interface but opens up to the importance of perception in meaning-making (Noë, 2009; Johnson, 2018) and perceptual learning (Gibson, 1963). To render the Cube Performer a creative machine performer, we are developing an expanded mapping interface that allows us to study the intertwinement of movement, perception, and situated meaning-making.

Like embodiment, a robot’s perception is radically different from human perception, independent of how humanlike or machinelike it might appear. Hence, while humans and robots may physically share a social space, from a biosemiotic viewpoint, they are each embodied in their own unique *umwelt* (Uexküll, 1957; Ziemke and Sharkey, 2001). Hence, meaning-making between humans and robots is an intra-bodily enactment across differentiated ecological niches. To afford dancers an embodied insight into the Cube Performer’s unique machine *umwelt*, PBM’s embodied interface is extended to allow for mapping between human and nonhuman perceptual worlds.

Relational Body Mapping (RBM) expands the PBM costume with an identical set of sensors as those used by the robot[31] to enable the dancer inhabiting the costume to experience the robot’s sensorium, made “tangible” to the dancer in the form of a dynamic soundscape. The RBM costume thus becomes a performative sensorial mapping instrument for enactive investigations into how movement shapes perception (Noë, 2004; Noë, 2009). The purpose is to study the performer-in-costume creatively working with the asymmetries between the two perceptual worlds and how this affects their relations with the environment and its dynamic affordances and resulting movement qualities. This, then, will allow us to bootstrap the learning of the Cube Performer with the motion patterns of the performer-cube entanglement capturing its qualitative movement dynamics in relation to interactional and environmental affordances (see Gibson, 1979; Rietveld and Kiverstein, 2014) based on negotiated *umwelts* (by the dancer). We are interested in the Cube Performer learning a generalisable model of this situated and perceptually guided (see Lindblom, 2020) motion data, based on the dancer having access to the robot sensorium; I cannot yet speak to whether and how this expands the robot’s improvisational capabilities

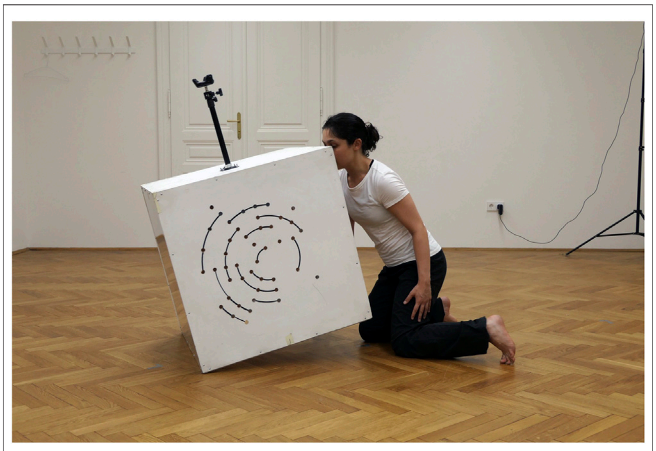

FIGURE 11 | *Dancing with the Nonhuman*, extended choreography experiment with A. Rochette (right).

as, at the time of writing, we are still in the process of developing RBM. The project also includes a research axis focusing on Laban/Bartenieff Movement Analysis (Laban, 1972; Bartenieff and Lewis, 1980) to produce descriptors used in a custom movement notation system and labels for the motion data used by the machine learner (see Karg et al., 2013).

The first stage of our performance-making process focused on developing a series of semi-improvisational choreographic scores[32] exploring the creative potential of relational exchanges between human and machine performers. These scores are enacted through embodied exchanges between a performer-costume entanglement intra-acting with another human performer (not in costume) (see **Figure 11**) and/or other artifacts and machine performers. Our RBM experiments thus expand our previous PBM studies by widening the relational scope to probe into the transformative potential of movement qualities with regards to the relational space between different agents, including artifacts, human performers, and their spatial relationships to a specific context. The relational space in-between agents here is understood as both an emergent result of the interactional exchange and a reconfigurable medium in itself that can be sculpted and rendered elastic through movement and its dynamic qualities of nearness, timing, and amplitude, etc. This tactile-kinaesthetic, spatial puzzle-solving and reconfiguring of bodies and things aesthetically put to work the asymmetries that arise from the different embodiments and perceptual worlds of humans and machines. Finally, our goal for the public performance work is not only to perform and evaluate our performance-making practice but to also become a research tool for involving the publics in

[31]Sensors include accelerometers, gyroscopes, magnetometers, depth cameras and a LiDAR.

[32]Developed in collaboration with co-investigator and choreographer Marie-Claude Poulin; see: http://www.konditionpluriel.org (accessed on 20 October 2020).

reimagining human-machine boundaries and promoting their elasticity.

DISCUSSION

This article has laid out a framework for *relational-performative aesthetics in human-robot interaction,* comprising a theoretical lens and design approach for critical practice-based inquiries into embodied meaning-making in human-robot interaction. The following takes a closer look at how movement qualities can contribute to human-robot interaction design and then identifies four areas of design challenges before ending with a summary.

The Relational, Situating Potential of Movement Qualities

In a relational-performative view, meaning-making is a fundamentally esthetic and embodied process, situated and unfolding in the interactional dynamics. Movement with its generative, dynamic qualities here offers more than cueing users "into what actions and interactions are possible" (Hoffman and Ju, 2014: 95). Robots with a heightened sensitivity toward motion dynamics and the mechanical abilities and improvisational skills to use them as building blocks for affective, social coordination could *generate* new meanings *with* their interactors, opening up aesthetically rich, social experiences without relying on predefined personalities, narratives, or tasks. The relational-performative effects of such skills are likely to be particularly useful in dynamic social environments where humanoid robots are too costly or potentially too risky from an ethical viewpoint,[33] or, simply, where more diverse robot participants are desired.

What bodily immersion, core to PBM and RBM, affords us is a viewpoint from within a specific machine embodiment and tactile-kinaesthetic access to its specific relational-environmental affordances (see Rietveld and Kiverstein, 2014). Techniques from animation (see Hoffman and Ju, 2014) and puppetry (see Jochum et al., 2017) or Wizard of Oz techniques, where interactions with design prototypes are mediated by a human operator (see Sirkin et al., 2016), also permit designers to project themselves into the artifact and offer powerful tools for creating expressive movements. The shapes and objects that can be imbued with life through these techniques can be surprisingly simple and abstract, as demonstrated in the classic animation of Chuck Jones's *The Dot and the Line* (1965). Animation often requires movement to be defined through static poses (keyframes) that are then digitally interpolated; we can find a similar approach in MIT's dialogue-free *Interactive Robot Theater*, which animated robot "actors" by transitioning between a set list of poses (Breazeal et al., 2003).[34] Yet defining movement through a series of static positions misses (out on) its "distinctive felt qualitative character" (Sheets-Johnstone, 2011: 122) and inherent, complex, and nuanced "spatio-temporal-energetic" (2011: 432) dynamic structures. We must not forget that *The Dot and the Line* is accompanied by a human narrator, a love story, and an expressive musical score. Granted, animation techniques, and underlying physics engines have much advanced since then, but a character's affective potential still relies on dramaturgically framing and timing it inside the bounds of the screen; e.g., in John Lasseter's *Luxo Jr.* (1986), "it was very important that the audience was looking in the right place at the right time" (Lasseter, 2001).

Physical puppeteering techniques, in contrast, connect the puppeteered to the human puppeteer in a shared physical space, although this connection is if often described as a form of manipulation—manipulating the puppet or its movable parts (see Piris, 2014), rather than extending into it/them. In our PBM studies, dancers sometimes chose to position themselves outside the PBM costume to, essentially, puppeteer it (opposed to inhabiting and moving *with* it). According to their own accounts, this felt more like attempting to control the costume, clutching it with their hands, arms, or legs and using their visual sense to explore movement patterns.[35] The entangled approach, in contrast, requires negotiation rather than control, which, we found, opens up a rich, ample landscape of affordances (see Rietveld and Kiverstein, 2014) from within. Drawing on my insights from our embodied design process and audience observations, I argue that the "spatio-temporal-energetic" (Sheets-Johnstone, 2011: 432) richness of movement qualities offers more than cues on possibilities. It *generates* possibilities by unfolding relational affordances that give rise to intracorporeal meaning-making, which is core to social understanding (Fuchs and Koch, 2014). The latter "is not an inner modeling in a detached observer," but rather the "other's body extends onto my own, and my own extends onto the other" (Fuchs and Koch, 2014: 6). Scaffolding the robot's learning by transforming human movement patterns in relation to the robot's unique embodiment, I argued, gives rise to a *bodying-thinging* in which a 75 × 75 × 75 cm cube-in-motion extends toward my body, and my own extends toward this other "bodying forth" (see Manning and Massumi, 2014).

Watching participants, whether as unsuspecting audience members or in studies, encounter our Cube Performer for the first time, one of the most common reactions, is surprise (see also Levillain and Zibetti, 2017). I am often reminded of Haraway's sometimes jerky, sometimes flowing dance that is embodied communication, where the dynamics unfold in unpredictable configurations and participants find themselves, alternating, in moments of harmony or "painfully out of synch" (2008: 26) with the cube. Some people reach out and rhythmically coordinate with its movements with their hand gently touching one of its sides.

[33]For example, in relation to vulnerable populations (see Šabanović, 2010; Turkle, 2011; Castañeda and Suchman 2014; Jones, 2018).

[34]For a more detailed discussion of animation techniques in relation to the affordances provided by performance-based techniques; see Gemeinboeck and Saunders (2106b).

[35]Based on my conversations with Tess De Quincey and Kirsten Packham. Video recording, 31 January 2017, Sydney (unpublished). See also Gemeinboeck and Saunders (2017).

Others prefer to step back and observe it for a while, usually circulating around it. Quite often, something makes them smile at the artifact or elicits a giggle. Participants also often crouch to match the Cube Performer's height or, more rarely, even take turns with the cube on their hands and knees whilst trying to keep up with its, at times, quick accelerations. In general, people either leave within 2 min or engage with it for more than 5 min, sometimes significantly longer. In the latter encounters, we found the following characteristics: interactors are 1) occupied with probing how the robot "works" and/or how they are being sensed, 2) engaged in an interplay of following the robot's movements, even tilting with it, etc., and attempting to elicit responses from it by moving in unexpected ways, or 3) inquisitive regarding its workings at first and then seemingly begin to settle and move in accordance with the robot (similar to 2). Interactors we talked to referred to the Cube Performer in surprisingly affective terms, using words like "gentle," "timid," "aggressive," "competitive," "cheeky," or "playful" to describe the ways in which it moves. Although the robot still lacked improvisational skills at the time of these public encounters, many participants related its movements to their own. Talking about having felt observed by the object, one participant said, "I know it's very connected . . . it's obvious that it does what it does because I'm here." To another, the cube came "across as playful with an 'honest curiosity'." Another commented, "I was sort of surprised about how intimate it felt . . . I felt quite tender toward it."

Design Challenges

The bodily, kinaesthetic immersion, which is at the core of our PBM and RBM mapping instruments, renders them very specific and is not feasible or practical in any design approach or for any potential robotic form. My account of designing with these embodied interfaces, however, offers the more readily transferable insights that careful attention to movement qualities in relation to a robot's specific embodiment can contribute to 1) situate abstract robots and 2) generating meanings as part of the interaction process. My notion of *designing with* suggests that we place more attention onto the embodied, imaginary and material meaning-making encounters afforded by the design process itself and how they shape the robot's social abilities.

Even if we have the opportunity to work with professional movement experts and wearable costumes or prosthesis-like attachments (see Gemeinboeck and Saunders, 2017) or any other types of mock-ups that performers can be creative with (see Hoffman and Ju, 2014; Sirkin et al., 2016), the delay between this, often, improvisational process and the technical development is significant. That is, the various technical design, prototyping, and machine learning stages involved in robot-making cannot keep up with the pace in which embodied knowledge and questions are produced in the experimental process with the performers. This inevitably slows down and, at stages, compromises the necessary and rich knowledge transfer and feedback loops between experimental and technical processes and the embodied insights they offer.

Studying the social, relational and performative effects of agential enactment as they unfold in the interaction dynamics is very challenging. As we aim to give ample space to meanings and relations emerging and being negotiated in the encounter, there are no specific tasks or predefined social capacities against which we can measure how well the robot or a human-robot-coupling performs. Observed relationships often do not discriminate between relations that emerge from within the encounter and ones that arise (only) in the eye of the observer. While we found that participants asked about their experience often were able to identify salient moments that triggered something, they may find it challenging to further articulate what happened in these moments of dis/connectedness, particularly in the first encounter. Also, as we look at meaning-making unique to each encounter, results are not as decisive and comparable as in more typical study setups. These challenges, however, are not only reserved for studying performative relations with machinelike artifacts but tend to arise when studying the complex dynamics of social interactions as situated couplings (see Bombari et al., 2015; De Jaegher et al., 2017).

Tightly interlinked with the above is the challenge that we can no longer control or predict what happens in the encounter nor whether or how meaningful social relations emerge. From a traditional engineering viewpoint, this may sound like something that only an artistic project can afford or even desires. Indeed, MML deliberately pursues design strategies that render our intra-actions with machines more emergent, open, and potentially ambiguous and definitely irreproducible (see also Levillain and Zibetti, 2017). I recognize that this is not a feasible or desirable strategy for any robot design or human-robot interaction scenario. But, I also strongly believe that we can only advance our knowledge about possible, meaningful relations with machines and what a robot *could* be, if we invest in more diverse and differentiated approaches into *designing with* a machine's social potential.

SUMMARY

My relational-performative framework understands aesthetics as central to our embodied meaning-making in human-machine relationships. Agency and, with it, sociality are enacted in the situated dynamics of the interaction itself, which moves the design focus into the middle of the encounter. Drawing on a performative new materialist account and embodied, enactive meaning-making, possible human-robot relationships are not a matter of design but rather are to be negotiated and *designed with* to give ample space to the interactional situation and the transformative potential of its social dynamics. Integral to this transformational process is the potential for *bodying-thinging*, where relations are not the product of meaning-making experiences but instead constitute meanings and experiences and, with them, subjects and objects. *Bodying-thinging* foregrounds both human and nonhuman capacities to extend toward and across boundaries and, doing so, destabilizes and potentially collapses binary opposites (Fischer-Lichte, 2008). A relational-performative aesthetics thus counters fixed, superficial esthetic mappings in human-robot interaction design and demystifies the figure of the robot as an independent, autonomous agent.

My notion of *designing with* proposes that we find ourselves in the midst of “the encounter” from the early stage of the design process. This is where we begin to manifest boundaries that shape meaning-making and the potential for emergence, transformation, and connections to arise from intra-bodily resonances (*bodying-thinging*). Discussing creative motion-centric approaches that put aesthetics to work to reimagine human-machine boundaries, I explored different perspectives on agency and how it constitutes the robot/machine as performer. My collaborative Machine Movement Lab project opens up an intimate link to performance-based inquiries into the relational enactment of human-robot encounters, based on an aesthetics arising from difference in relation. The Performative Body Mapping (PBM) methodology harnesses dancers’ tactile-kinaesthetic expertize and the sociocultural dimensions of (human) movement qualities to socially situate an abstract robotic artifact and bootstrap its machine learning. Relational Body Mapping (RBM) extends the PBM costume to serve as an instrument for sensorial mapping between different human and nonhuman perceptual worlds. MML’s overarching aim is to open up new pathways for robot design by focusing on the coupling of human-machine and “giving space” to the enactment of relations and the emergence of meanings in the encounter.

According to Suchman, reconceptualizing how we conceive of “the human, the technological, and the relations between them [has] implications for everyday practices of technology design” (2007b: 139). Reconceptualizing our relations with robots and how this implicates and transforms our design practices has been the main focus of this article. How such alternative practices can affect new kinds of relationships with robots will require significant investment into studying differentiated and diverse design approaches as well as involving potential users from the early stage of the design process. Creative practices expand technology design not only by bringing different cultural and esthetic questions to human-robot interaction research but also by engaging the publics in the important question of how machines *could* socially participate in our society.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the articlel; further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Human Research Ethics | UNSW Research. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

PG was the sole author of the submitted manuscript and holds the copyright for **Figures 1-9** and **11**. L.-P. Demers holds the copyright for **Figure 10**. The author has been given written permission by L.-P. Demers to publish **Figure 10**. Reproductions of this article must include copyright notices for Figures.

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Babyface: Performance and Installation Art Exploring the Feminine Ideal in Gendered Machines

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Representations of gender in new technologies like the Siri, Pepper, and Sophia robotic assistants, as well as the commodification of features associated with gender on platforms like Instagram, inspire questions about how and whether robotic tools can have gender and what it means to people if they do. One possible response to this is through artistic creation of dance performance. This paper reports on one such project where, along the route to this inquiry, creation of machine augmentation – of both the performer and audience member – was necessary to communicate the artistic ideas grappled with therein. Thus, this article describes the presentation of *Babyface*, a machine-augmented, participatory contemporary dance performance. This work is a reaction to feminized tropes in popular media and modern technology, and establishes a parallel between the ways that women and machines are talked about, treated, and – in the case of machines – designed to look and behave. This paper extends prior reports on the creation of this piece and its accompanying devices to describe extensions with audience member participation, and reflect on the responses of these audience members. These fabricated elements alongside the actions of the performer and a soundscape that quotes statements made by real "female" robots create an otherwordly, sad cyborg character that causes viewers to question their assumptions about and pressures on the feminine ideal.

Keywords: robotics, art, design, performance, embodiment, breath, HRI, gender

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1 INTRODUCTION

Tools have long been a part of performance. For example, we are familiar with a knife in the hands of an enemy signaling danger for a protagonist. Such tools have frequently been a part of dance productions as theatrical props that afford new movement on performers' bodies. For example, a sword makes stage combat an evident plot line as well as a beautiful choreography of bodies acting in support of long linear lengths of metal. Many of the tools we use today, smart phones, computers, and fitness trackers, and the tools we may use tomorrow, household assistants, robotic prosthetics, and self-driving cars, have not been explored as much in dance performances. Many of these tools have hidden internal workings and do not yet exist, requiring new strategies, characters, and perspectives for incorporating them into dances. Further, such tools as knives, computers, and robots, are often associated with the male gender, as reported in Lerman et al., (1997) and Kelan (2007). Thus, they read differently in the hands of feminine performers and as such create compositional challenges in commenting on feminine experience with these tools.

Our tools have always been "other" to our "selves", but as these tools grow in complexity and are developed through increasing specialization, these tools have taken on a new level of other-worldliness. Therefore, creating motion with the medium of robots inside performance poses challenges for seamless presentation inside the performance's aesthetic. If the machine is symbolic of bigger ideas or textures, then the viewer must become attuned to its strangeness. If the performer is to be able to execute correctly, they must be trained on working with and around the devices. If the pair can escape the literal spectacle of human-machine interaction, there is hope to be able to express new ideas through both human and artificial bodies onstage.

Thus, this paper presents *Babyface*, a performance art installation shown in Wellington, NZ at the 2020 Performance Arcade. The work extends previous performances, described in Ladenheim et al., (2020), with two breath-triggered machines: one, a pair of wearable wings for the performers and controlled through their bodies, and another, a wall-mounted kinetic sculpture that participants could control through their bodies. This paper will describe the installation work and provide commentary on the unique creative challenges posed by the goals of *Babyface*, which includes machine movement to 1) bring topics of technology, control, and limitation to the stage in a physical manner and 2) offer audience members the feeling of unexpected intimacy with technology. The goal of these inclusions is to allow the piece to comment on society's relationship with technology and gender more broadly, and to allow individual audience members to re-frame their own experiences with machines and gender representations within them.

The paper is a first-person description of creative practice inside research and development of novel robotic systems (rather than a scientific study on human subjects) and is structured as follows. Background literature is organized and reviewed in Section 2. The development of an onstage cyborg character and its machine augmentation is described in Section 3. Extending this work to an interactive installation – through both an extended choreographic frame as well as new machine development – is described in Section 4. Creative reflections and discussion, from performer, participant, technologist, and artist points of view, are offered in Section 5[1]. Broader takeaways for other artist-robot teams are suggested in Section 6. Finally, concluding remarks are offered in Section 7.

2 BACKGROUND

This work sits inside a long tradition of creation and experimentation with machines alongside human bodies and femme representations. In this section we review prior literature that has explored the intersection of gender and technology, human augmentation with machines through embodied design, and robots inside live and installation-based art.

2.1 The Cyborg Metaphor

In her seminal text The Cyborg Manifesto, Haraway (2006), Donna Haraway states:

"The cyborg is a kind of disassembled and reassembled, post-modern collective and personal self. This is the self feminists must code."

Haraway's work, originally published in 1985, is eerily predictive; if then we were inextricably linked with our machines, now we are even more so. Particularly, the widespread adoption of smartphones and social media exerts great influence over our actions, motions, interactions, and presentation. Depictions of the feminine ideal abound on these platforms — smiling, retouched women in meticulously styled environments, crafted and shared in service of the male gaze, parade as normal, even expected. Our work responds to this implied expectation: that we ought to move and present as machines suggest. This feminine ideal, in turn, is performed by robots and coded by their creators, reinforcing patriarchy and bringing it more deeply into the realm of the physical.

2.2 Gender Representations in Technology

Londa Schiebinger's work delves into the complexities of gender norms, identities, and relations in robotic design and other technologies, arguing that there is an opportunity to challenge gender norms in robotic design by disrupting the "matching" of traditionally gendered roles to their robotic representation, Schiebinger (2008). This work has been completed inside the aforementioned ecosystem of technologies that present as "female" to align with notions of service in feminine stereotypes.

From an aesthetics perspective, Sianne Ngai's scholarship is also instructive. In Ngai (2012), cute is defined as "an aesthetic disclosing the surprisingly wide spectrum of feelings, ranging from tenderness to aggression, that we harbor toward ostensibly subordinate and unthreatening commodities." Ngai comments extensively on the power cuteness has to be simultaneously sexualized and non-threatening; feminine robotic performances can also tread this line. While Hanson Robitics' Sophia performs uncanny technical prowess, she proclaims herself "happy to be a magic spectacle" and is described as "attractive" as analyzed in Retto (2017). SoftBank Robotics' Pepper, while referred to by SoftBank as "he," is a service-oriented robot with emotional sensitivity, and is designed with feminine curves, a cinched waist, and wide eyes (Van Wynsberghe (2016); Soraa (2017)). These gender divides are further underscored by disembodied virtual assistants, for example Apple's Siri, Amazon's Alexa, and Microsoft's Cortana, whose voices are, by default, feminine sounding and friendly. This adoption of cuteness helps these machines remain widely accessible and well-liked.

2.3 Somatics and Design

The field of somatics has worked to formalize and codify the conscious experience of bodily movement. Methodologies include various forms of yoga as described in Fraleigh (2015),

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Alexander Technique as in Gelb (1995), Bartenieff Fundamentals as in Bartenieff and Lewis (1980), the Feldenkrais Method as in Rywerant (2003). As described in Hackney (2003) and Nettl-Fiol and Vanier (2011), these somatic practices and theories have contributed to refined perspectives on dance training as well.

Beyond influence of physical practice, somatics have also found notable influence inside the space of design, including the design of robots. For example, a "smart" rug and lamp designed for IKEA is described in Höök et al., (2016). From pioneering projects like this, principles of somatic product design and aesthetics have been formulated as first in Höök et al., (2017) and later expanded on in Höök (2018). Design practices guided by this work consider the centrality of the movement of breath in human experience – a motion often overlooked by even sophisticated external measurement systems like motion capture studios.

For example, using the somatic practice of Bartenieff Fundamentals to form the basis for investigation of bipedal robotic gait in Huzaifa et al., (2016). This led to multiple modes (or "styles") of walking gaits established and validated in Huzaifa et al., (2019b) and novel biomimetic hardware design implemented in Huzaifa et al., (2019a) that promoted the role of the spine in walking, despite its small displacement relative to lower limbs. Similar investigations have also noted the importance of the spine in communicating intent as in Corness and Carlson (2019).

2.4 Human Augmentation With Machines

Many wearable robotic devices offer highly specific, functional purposes; as in robotic prostheses or The Sixth-Finger; designed by Prattichizzo, Malvezzi, Hussain, and Salvietti. This device adds another robotic digit to a human hand, which allows for greater capacity for handling large objects. Similarly, Arque is a wearable tail that reacts to a user's shifting center of gravity and enhances balance, as in Nabeshima et al., (2019). The functions of the Sixth-Finger and the Arque are dependent upon the user's actions; by responding to their movement these machines can deepen the expression of the user's intention.

This deepening of expression occurs in artistic works involving wearable robotics as well. As in Sonami (1991), the Lady's Glove serves as "a response to the heavy masculine apparel used in virtual reality systems," and uses glamorous materials to design an instrument where hand motions alter sound. Rosa Weinberg and Laura Zittrain's *Stethosuit* also creates sound from the body, this time using stethoscopes to pipe sound into the wearer's right ear while pre-recorded sounds from space pipe into the right. This creates a fashion-forward conversation between experiences within and without the body. In Caroline Yan Zheng's *Extimacy,* humans wear touch-responsive soft robotics reminiscent of corals, worms, or aliens. According to the artist, this prompts questions about "the robot as part of our body and 'prosthetics' as an expressive or signifying system." Additionally, Anouk Wipperecht's "Spider" Dress, as in Svadja (2014), creates mechanical boundaries of personal space. When the wearer is approached aggressively, the dress's attachments assume an attacking position, signaling others to keep away. When the wearer is approached calmly, the limbs instead create smooth gestures, allowing for closeness. The device also takes into account the wearer's breath in its defense posture. In this case, the wearer's reactions, the motion of the dress, and the interactions of people around the wearer create a conversation based on intentionality, emotional state, and expressive motion. These explorations by practitioners and artists have begun to be codified by academics as well as in Guler et al., (2016).

2.5 Robots in Performance

Robots have been leveraged in performance both by artists, extending their onstage material, and by researchers, working to extend and test the capacities of algorithms and hardware in a performative setting, often blurring the line between both. The work presented in this paper extends one such performance discussed in Ladenheim et al., (2020).

The artist Stelarc has used machines in numerous modalities, including as a large, wearable exoskeleton that he battles with onstage; some of his perspective on working with these machines is described in Candy and Edmonds (2002). On stage performance with a large robotic arm by Huang Yi, described in Bruner (2018), featured by TED as well as a small humanoid by Bianca Li featured at the Brooklyn Academy of Music. In creating "ROBOT" Li was quoted by the New York Times: "No machine will ever be so amazingly rich in movement." And through the making of 'ROBOT,' she said: "I rediscovered dance. I realized how rich it is." – from Kourlas (2015).

Examples where the research point of view has been foregrounded include investigations of how bodily motion of dancers can generate motion for nonanthropormorphic artificial bodies directly as in Gemeinboeck and Saunders (2017). In addition, researchers have worked to formulate systematic, parallel data collection during performances featuring robots as in Cuan et al., (2018). Likewise, in the space of comedy, reactive algorithms that leverage active audience response, have been proposed as in Vilk and Fitter (2020). Researchers have also looked into the space of theater and acting as a source for material as in Fitter et al., (2017).

2.6 Interactive Installations

Interactive installations have long been used by artists, researchers, and educators alike to create lifted versions of reality that express points of view, test new interaction modalities, and teach new concepts. To the latter, Lindgren and Johnson-Glenberg (2013) describes how embodied installations embolden learners to better support the ends of educational goals. Researchers have posited adaptive algorithms that re-position elements of museum installations based on the flow of people through the exhibit – active elements that can also become part of the exhibit itself as in Godbehere and Goldberg (2014). Learnings from museum-based installations have also influenced the design of public installations, like those in the Performance Arcade as described in Hornecker and Stifter (2006).

Dancers have created permanent installations with robots that can translate their choreographic designs to ongoing, "always on" physical performances as William Forsythe did in 2014 with the premiere of *Black Flags* that has since appeared in multiple museum spaces. Similarly, *Mimus* by Madeline Gannon, JuliÃ¡n Sandoval, Kevyn McPhail, and Ben Snell, was commissioned by The Design Museum in London, UK in 2016 for their exhibition, *Fear and Love: Reactions to a Complex World*. Such installations have also been paired with human-robot-interaction studies as in *Time to Compile* described in Cuan et al., (2019).

3 Breath-Activated Extension of a Machine-Augmented Solo

Bolstered by past work and precedent spanning gender theory, somatic design, robotics in performance and interactive installations, this section describes the creation of a performance work that uses a physical human augmentation onstage to create a hyperbolic, feminine cyborg character. This performed character allows the piece to reference existing feminine coding in machines. Connecting the action of the performers breath to the machine allows us to create a convincing cyborg, one whose motion seamlessly translates to worn augmentation. It also suggests, as the piece progresses, that the human performer is flattened, exhausted, and restricted due to this physical-ized stereotype and societal coding.

3.1 Prior Work in Creating a Cyborg Character

Prior work, Ladenheim et al., (2020), presents the creation of this stereotypically feminine cyborg character through artistic and robotic development. In a 5 min piece performed in the Dance NOW Festival at Joe's Pub at the Public Theater in New York, NY, an onstage performer (our first author) exhibited choreography while controlling robotic wings with a small handheld button. This performance served as the basis for the work described here.

The design of the performed character (including robotic design, choreography, costuming, sound, and character development) balances expressive grandeur and physical restriction. The work references the exaggerated, performatively feminine characteristics in existing robots and digital representations of women. Artificial Instagram influencers like Lil Miquela, video game characters like Mercy in Overwatch, AI chatbots like Mitsuku, and robots like Misty perpetuate limited stereotypes, despite their impressive technical innovations and contributions.

In extending this initial work, we wanted to free the performer's finger of subtly pressing the handheld button and allow many lay participants to experience a similar "performance" of robotic control. This required development of new sensing systems to support, which are described in the next section. We then developed a participatory installation for staging at multi-day outdoor container-based event as described in Section 4.

3.2 Enabling Robust, Adaptive Breath Detection

Although we used a push button sensor for the performance in Ladenheim et al., (2020), ultimately, we wanted to enact an embodied semi-conscious channel between the performer and the artificial wings. Our goal was to both provide an active channel where the performer could voluntarily trigger the motion of the device as well as a channel where sometimes the wings moved without the performer consciously choosing their action. Breath is such a somatic channel. As promoted by Hook's somaesthetic design methodology, described in Höök (2018), this design choice required reflection on our own physical situation in our own lived bodies. This choice is also based on our training and experience in somatic practice, where the primacy of breath in creating bodily movement is stressed, e.g., as in Nettl-Fiol and Vanier (2011).

Our concept in developing a wearable, non-invasive breath detector is the detection of the motion and deformation of the torso that is used to change pressure inside the body cavity and produce the desired exchange of gases for breath, which we measure with existing sensor technology in novel bodily placement and integration. In a simple model of an inhale action, the diaphragm (a muscle that bisects the human body around the location of the T-12 vertebrae) presses downward, condensing the viscera beneath and lowering the air pressure in the lungs, causing an intake of breath. In an exhale, the diaphragm presses upward, releasing pressure on the internal organs below, e.g., the digestive tract, increasing air pressure in the lungs and creating an outward flow of air from the body. This process also produces uneven radiation in and out of the torso.

Commercially available systems for detecting breath leverage bulky hardware that is closed-source and often renders the wearer with limited mobility. However, pressure sensitive materials are easy to purchase, fabricate, and integrate into an electrical circuit. An early prototype used in rehearsal for *Babyface* critically impacted the choreography and created character described in Ladenheim et al., (2020). It utilized a similar design that was difficult to reliably calibrate and configure beneath the wing harness. This arrangement used a linear mapping between a fixed threshold of pressure detected by a force sensitive resistor and the range of motion of the servo motors powering the wings. That is, the fixed, predetermined range of the pressure sensor was mapped linearly to the range of the servo motors.

For more robust performance that would translate across multiple bodies (as the piece was set on new performers and later for participants engaged in our interactive installation), we needed an adaptive breath detection system with a simple, robust sensor. Thus, we utilized patches of flexible conductive fabric, Velostat. Since this material changes its resistance under pressure, it was used to create a pressure-sensitive circuit.

As shown in **Figure 1**, we collected resistance readings using the analog input of the Arduino micro-controller and at multiple points on the body, noting the differences in shape deformation that occur around the torso (later, we will see that this shape change can be different person-to-person as well). Through this experimentation, we settled on targeted breathing modalities for performers and participants: performers would activate their wearable wings using a "rib breath" and participants would activate a section set of stationary, wall-mounted wings, described in the next section, using a "belly breath".

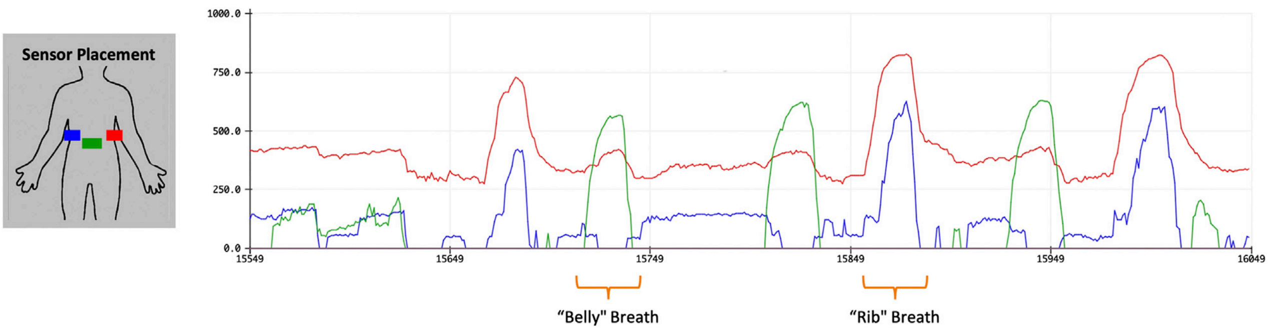

FIGURE 1 | Testing multiple sensor placements in order to determine feasible placements.

To detect these events each had a distinct sensor placement. Performers placed the sensor on the right side of their ribcage, where the sensor could be integrated to the wing harness without being under constant pressure, e.g., due to straps holding it in place. For participants, we placed the sensor just below the sternum on the soft part of the upper belly, allowing for attachment straps to run along the ribcage just under the breasts of participants, accommodating many chest shapes and sizes.

Finally, an adaptive threshold was used to detect breath events. The sensing system updated max and minimum detected pressure on the sensor every ~15 sec (75 cycles of the microcontroller with a 200 msec delay), creating a threshold for recent action to trigger motion in the wings. For performers, the same linear mapping between the maximum range of the pressure sensor (which is now variable) and the maximum range of motion of the wearable wings used in Ladenheim et al., (2020) was used.

This is a very rapid and relatively short window for adaptation that, for example, allowed performers stuck in a side bend for the length of several musical phrases where their ribs did not physically expand as much as in a neutral posture to successfully trigger motion in the wings. Moreover, when used on a variety of participants, this adaptation allowed for a short calibration period where participants could trigger the motion of the machine and understand how the actions of their belly were impacting the installation.

4 DEVELOPMENT OF INTERACTIVE INSTALLATION AND PERFORMANCE

Our work was invited for participation and presentation at The Performance Arcade in Wellington, New Zealand, February 26 – March 1, 2020. The arcade is an outdoor performance festival with site-specific artworks taking place in shipping containers along the Wellington Waterfront, a public space situated along the Wellington harbor. The Arcade estimates about 60,000 audience members annually. For this engagement, we needed a installation that fit inside of a standard-size shipping container that could run for 13 h a day. Further, the work needed to be constructed, rehearsed, and tested in 3 days time, creating unique design and choreographic challenges for the work, which we discuss here. To supplement the following discussion, images from the performance and installation in day and night lighting conditions are shown in **Figure 5**.

4.1 Robot Design

With our adaptive sensing system, we could now rapidly calibrate our breath sensor to many body sizes and shapes, allowing for the development of an interactive, breath-activated experience. An obvious, initial idea was to have participants wear an extra set of wings like the performer. However, getting in and out of these wearable wings takes practiced performers 20–30 min, which was not feasible for participants. Moreover, we needed to establish a setting for our performance in the shipping container, something that answered "Where is the cyborg character?". Thus, we began thinking about the massive landscape of the internet, where images of feminine perfection are celebrated with, often half-consciously made, "likes", "retweets", "comments", and "shares". We also wanted the installation to give people the experience of controlling a large scale machine and to feel their part in celebrating the hyper-femme.

To facilitate this interactive experience and to create this setting for our performance, we designed a wall-mounted robotic system that would serve as participants' "wings" as well as an animated backdrop for the performer using the following design goals:

- rapid safe onboarding of participants of many shapes, sizes, and needs, considering tripping and shock hazards
- rigid, machine-like, and futuristic aesthetic
- tolerant to outdoor, windy conditions
- a reference to the experience of looking into a mirror or cell phone and practicing the presentation of oneself (a surface for "posing")
- large-scale movement with intuitive, breath-activated control by participant
- modular and scalable to mitigate unforeseen installation issues onsite
- facilitation of participant awareness of how and when they were controlling the machine, playing at the boundary of conscious and semi-conscious control, echoing

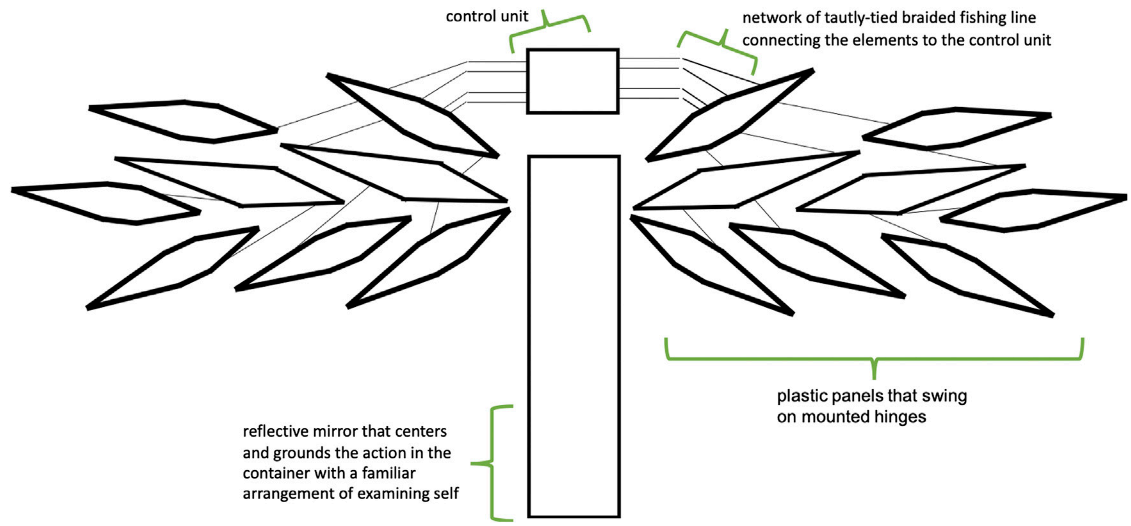

FIGURE 2 | To-scale schematic of mounted wings for *Babyface* installation.

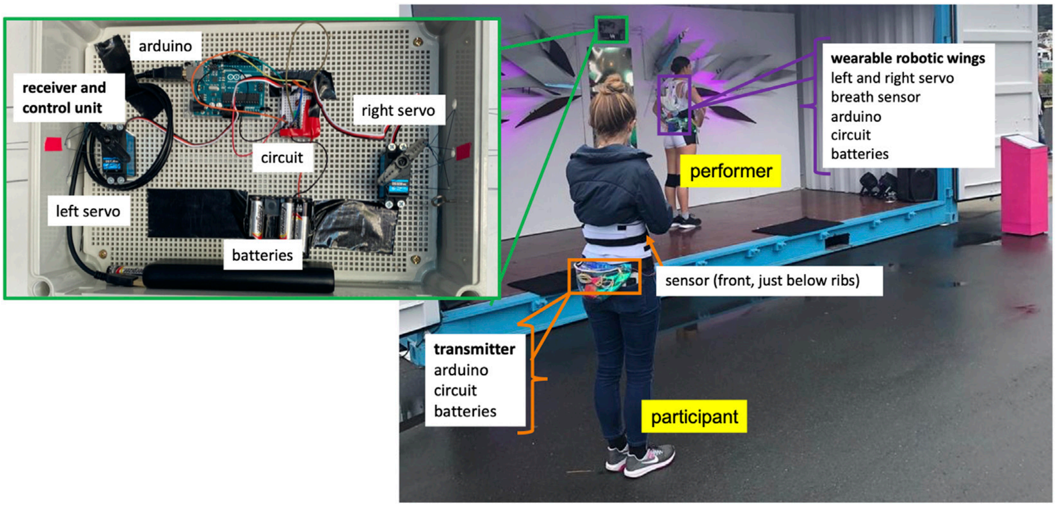

FIGURE 3 | Arrangement of electro-mechanical elements and human interactants in *Babyface* installation.

the relationship we have with smart phones and other ubiquitous machines.

Answering these constraints, we created a series of mounted wall elements, built in the shape of two abstract wings and interconnected with strings, that would move in response to a wireless breath-sensor worn by the participant. We designed shard-like elements that could each move independently or as a single unit to simplify the design, creating a movable mosaic that represents the kind of multifaceted impact of a single semi-conscious internet post.

Arrangements of final shard design, as well as an expanded future design, are shown in **Figure 2**. Each shard was tied tightly to a metal harness tied to an active motor unit. These can be operated by one to six servos on a single Arduino microcontroller, and with wireless communication between multiple boards, we can easily scale that number for sites that allow more elements to be installed. At the Performance Arcade, we used two servos on a single board, mounted in the center of the container and left open for viewing to accentuate the machine-like aesthetic (shown in **Figures 3,4**).

Designing the motion of the wall was a balance between time constraints on the installation setup itself (2.5 days) and requirements on robustness (the installation ran 5 h on its opening day and 13 h a day for 4 days longer). Moreover, we wanted the participant to clearly register when they had triggered the machine to create that feeling of control. Further, we needed to accommodate many body sizes and skill levels in breath control. Thus, we wanted a high degree of contrast between simple on and off states.

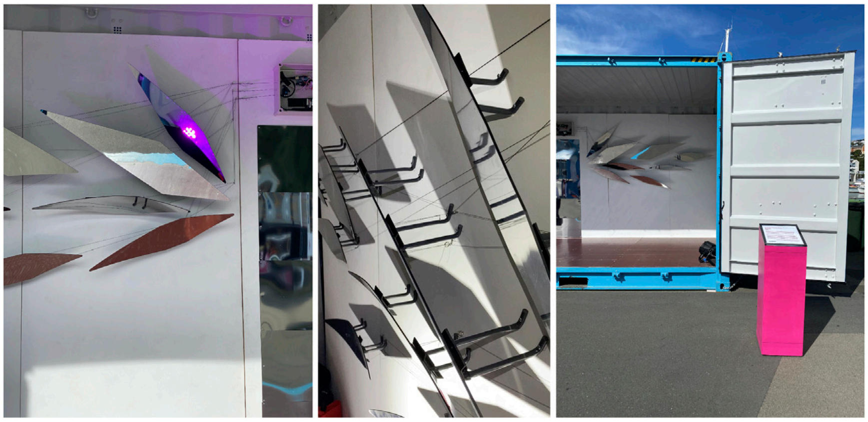

FIGURE 4 | Textures and composition of structural elements of *Babyface* installation.

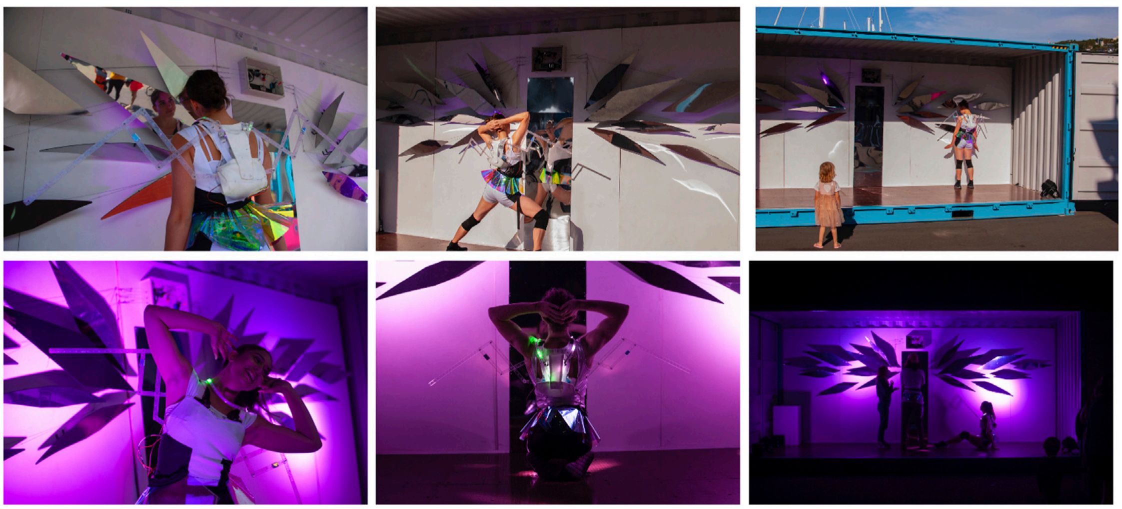

FIGURE 5 | Images (day and night) of the Babyface installation, which ran from 10am to 11pm. Photos by Colin Edson.

The final motion design was for the shards to be held in a flat position, parallel to the wall until triggered by the breath sensor when they took on a rapid, monotone fluttering motion until the sensor transmitted an 'off' state cue. The breath sensing system used the same adaptive threshold for action as the performers, triggering only when the participant was in the top 33% of the range. Thus, the wall would move when the participants' belly was most extruded from the spine, creating pressure on the sensor and typically corresponding with an inhale, while quieting to stillness on the exhale. Notably, not all participants' breath patterns behaved in this manner, and a hand full of participants experienced the opposite behavior through sucking their bellies in on their inhale and relaxing them on their exhale.

4.2 Participant Onboarding and Experience

The robotic sculpture creates a traditional spatial arrangement of a performer on a dedicated stage space, even as the performance exists in an nontraditional outdoor setting inside a shipping container. The short participatory experience for audience members curious for more interaction thrusts them into this presentational frame. During these individual experiences, the container remained open and in view of onlookers and passersby. The experience needed to fit inside this aesthetic and theatrical frame, while also allowing for more functional explanations of the setup and accommodating the comfort of participants. To satisfy these constraints, which are somewhat at odds with each other, we minimized the setup and calibration times and established a similar performative frame for participants. The structure of this is outlined below.

- ***Onboarding***

The audience member approaches the installation, sees the mirrored wings and the performer in relation to them. They are invited by an usher to try the wings on themselves, to activate the fragments on the wall that can move with their breath. In this interaction, it was essential for the usher to act simultaneously as an informative resource, giving the participant necessary information about the process of experiencing the interactive installation, and as a collaborative member of the performance team, sharing information inside the performance frame. For example, this docent would say "Just as the performer is wearing wings triggered by their breath, you can try on the wings mounted to the back of the container, and trigger them with your breath, by wearing this [presenting the device] sensor." This both informs the participant about the inter-workings of the installation, such as method of control, while maintaining the theatrical frame of wings (neither what the performer was wearing nor the mounted elements in the container were real "wings").

- ***Sensor Fitting***

If they accept, the assistant will help them wrap the participant in a wide black cloth with the velostat sensor embedded inside. The participant would hold the sensor at the top of their belly, just below their ribs, and the docent walked around the participant, wrapping them in the rectangular piece of stretchy fabric, allowing the participant to apply pressure to attach the fabric with strips of integrated velcro. The usher needs to ensure that the straps do not apply constant pressure to the pressure-sensitive area, which maxes out the readings, reducing the range of activating and diminishing the desired effect. This procedure, allowing the participant to secure the sensor themselves, ensured personal comfort and minimized inadvertent touch in a sensitive bodily area. When contact was necessary, the usher would ask if it was okay to touch to assist. Then, the usher would turn on the sensor by plugging the micro-controller into the battery, both stored inside an integrated fanny pack. Leaving the sensor-transmitter system off during fitting reduced inadvertent firing of the wall.

- ***Calibration***

The usher next led the participant through taking a few stabilizing breaths while the algorithm adjusts to their pattern and range of breath. Inside this interaction, the docent establishes the participant's conceptual mapping to the affordances of the interface. The assistant is watching, waiting for the thresholds to adjust to this participants' range of motion and associated pressure on the sensor. Then, they explicitly point out to the participant how the mounted elements begin fluttering at their motion, establishing the participant's sense of control. On their inhale, about two-thirds of the way through, the wall would trigger, beginning a rapid, even fluttering of the wall elements; on the exhale, about one-third of the way through, they would still, holding steady in the "flexed" state, where the elements faced parallel to the wall, creating a fractured mirror surface. This experience was best for participants that were able to use the motion of their middle abdomen to create their breath, which could often be enhanced through shifting the location of the sensor, and for a few participants, the activation occurred on the exhale inside of the inhale.

- ***Exploration***

At this point, the docent would explain "You're now in control of the wall and the space is yours. You may explore and interact with the performer – and if you like, I can play a track that will lead you through some choreography." About one-third of participants would agree to this suggestion, sometimes with nervous laughter aimed at friends in the audience, sometimes with awestruck severity remaining in the internal mode of the calibration, and many other reactions, proceeding to the experience described in the next bullet. Those who stayed in the exploration mode would typically stand in front of the wall, observing their reflection in the mirrored surfaces and the movement of the performer.

- ***Performance***

The participant is guided by a high-pitched, servile female voice, and asked to place their hands on their hips and spread their feet apart. This position introduces a feeling of vulnerability – similar to stepping into a body scanner at an airport. Then, the participant is asked to move their hip to one side as they look up and to the right. They are told to take a breath in and out, and told they look beautiful. They are also asked if they feel beautiful. These instructions continue, leading the audience member to a position with their feet spread apart, hands behind their head, breathing in and out as they move their hips side to side along with a driving pop beat, wings fluttering on the wall. At this point the vulnerability and sense of exposure is heightened considerably from the opening, but it has built slowly, with innocent-enough requests that, by the time the participant is banging along with the music, they feel quite exposed and even involuntarily sexualized. This sensation is designed to correspond with described conditions of cuteness as a product of objectification, as in Ngai (2012). Some participants (often, but not always, male-presenting participants) avoided this sensation with creative interpretations of the commands. These participants would manage to create right-to-left motion in their bodies that avoided protruding the pelvic girdle beyond its typical alignment with the femur. Some participants (often, but not always, female-presenting participants) relished this section of the choreography, finding a familiar pattern of bopping along to a good beat and feeling sexy. These participants would often ad lib to the basic requests and twist their body in screw-like shape forms that further accentuated the three dimensionality of their bodies.

- ***Audience Acknowledgment***

Once the music dies down, the audience member is told that they've done a great job and that they deserve to be celebrated. When they turn around, the other spectators are prompted to clap for the audience member, a "magnificent angel," and now a *de facto* performer. This moment could read a few different ways for the onlooking group. Occasionally, discomfort would descend on the group of onlookers, realizing the bodily objectification that the "performance" had led the participant through. Often, the audience would clap jubilantly, as if in on a wonderful joke or fun experience. But invariably, a few onlookers, who made themselves known to members of the creative team, would disapprove of this participation, noticing the feeling of forced puppetry that the participant was experiencing.

- ***Documentation***

The spectators are also instructed to take a picture of the audience member activating the wings, to "keep the memory of your splendor with you forever." This returned the participant to a more familiar frame, as though posing in front of a historic monument or beautiful vista. Participants posed with the performers and either the docent or companions would take photos.

- ***Offboarding***

The usher would then remove the sensor from the participant, allowing them to undo the Velcro and hand over the straps so that the usher could unwind the cloth. The usher would at the same time debrief the participant, asking how it went and what their impressions were. For the most part, audience members tended to frame these answers around one of two types. Either, they focused on their affective experience, noting emotional reactions, e.g., that they felt powerful, that they were embarrassed, that they were just amazed by the experience. Or, they framed their reaction as an intellectual curiosity, asking how the installation worked and whether the assistant helped build it.

4.3 Connecting Performer and Participant Through an Expanded Choreographic Frame

The performer's choreography extends the work from Ladenheim et al., (2020), with changes to fit the presentational frame of The Performance Arcade and to establish parallels between the performer experience and the audience experience. Notably, we offer the same questions and prompts to the audience as we do to the performer. In this way, we acknowledge the audience prompts as choreographic, and we offer the performer a character development opportunity to answer the questions through the lens of her own experience.

Questions mirroring the questions asked to the audience

The performer executes a series of motions led by a voice-over; breathing in and out as she looks at herself in the mirror, placing her hands on her hips and behind her head, moving her hips side to side as she breathes in and out. When performed by a highly stylized character, these prompts contain the air of a pre-show pep talk.

- ***Embodying the Stereotype***

The pep talk leaves the performer well prepared to embody the archetypal, idealized female; reassuring her that she can be magnificent as long as she tries. Immediately following, a hard-style, EDM beat drops, decorated with flourishes, beeps, and synthesizer tracks that bring up fun memories of retro computer games. The performer moves her hips side to side to this music, smiling as she layers a series of stereotypically feminine hand gestures and poses onto her upper body.

This section reads almost like a stop motion series of images: wink, selfie, teenage dream, virgin, prom photo, fashion model, pop star, pinup, superheroine, goddess, one after the other after the other. These fleeting images constellate the character as a whole: the "idealized" woman, built from an onslaught of images from history, art, and media, telling her how she ought to perform.

- ***Breakdown***

Where previously the motion, sound, and spectacle were in alignment, here the performance starts to depart from theatrical expectation. The rhythmic, driving nature of the previous section persists in a side-to-side bevel motion with the legs, while arm and head motions become increasingly erratic and jarring. In an attempt to pull herself together, the performer starts a side to side jumping pattern, picking up speed and frantic energy as the music breaks apart into screeches and crashes. With this more vigorous motion, the wings betray their actual fragility, contrasting how machine-like, strong and expansive they appeared when they were augmenting the controlled, archetypal poses. Now, they shift outside of the coronal plane, flapping awkwardly as the cyborg vigorously jumps faster and faster towards nowhere.

Once fully worked up, she pulls herself out of this pattern by smacking herself hard on her behind, then loses control again as she leans backward and forwards out of time with the music, her head and torso rolling like a rag doll.

Within empty white noise and clicking sounds from the music, the cyborg bobs aimlessly with her hands behind her head, scans the passing audience while searching for approval, and slowly builds herself back up to a standing pose; she's snapped back to, ready again to prove she's not broken.

Extended grappling with the limited presentation of the feminine

A disembodied, youthful-sounding, hyper-feminine giggle snaps the performer out of her stupor. With a fixed, creepy smile, she jarringly cocks her head to the side.

"I'm happy to be a magic spectacle, and I love it when I can make people laugh and smile," she says, one hand delicately placed underneath her chin, legs arranged into an alluring bevel. A series of flowing, breathy phrases are punctuated by intermittent quips from the hyper-femme, disembodied voice, mouthed by the performer in reference to existing systems like Siri, Alexa or Cortana. These movement phrases explore the places where cute gives way to creepy, expressive becomes overtly sexual, and attempts to feel empowered become desperate. When are the wings magnificent, and when are they just sad and absurd?

"It's a system… a system of rules and behaviors," the cyborg mouths to the disembodied voice echoing around her. She smiles, seated on her hip with a hand posed over her mouth. "If you're nice to me I'll be nice to you," she lip synchs, facing the back and spreading her legs and wings open. "You can treat me as a smart input output system!"

These words and motions swirl together, eventually bringing the performer back to the ground, in a splayed, broken position. Her back foot raises up and down as my head tilts side to side, wings moving eerily in and out.

- *Conclusion mirroring the conclusion of the audience experience*

As with the audience experience, the performer concludes by acknowledging the audience; having had a glimpse into the cyborg's story, the audience is now "ready" for her. She turns around, clumsily acknowledging her grandeur and asking for a picture from the audience.

5 REFLECTIONS AND COMMENTARY

This public presentation of art was not a systematic user study; however, in this section we provide reflections on the robotic installation and accompanying performance, offering a creative perspective on this work as well as insight into design challenges. Rather than an empirical experiment with human subjects, what we provide here is an explanatory analysis of our practice as a contribution to research. First, we provide a first-person point-of-view of the experience of performing the work. Then, we outline our experience in introducing this work to the hundred odd participants that experienced the installation interactivity in Wellington, NZ. Finally, we share perspectives on the creation, conception and reception of this work in full.

5.1 Performer Perspective

To date, five different performers have embodied this role of the cyborg performer. The following represents the perspective of the first author who choreographed and has also performed the work. As choreographer, performer, and rehearsal director, her experience of the movement is arguably the richest and most nuanced; thus we select her perspective, which is only one of many, to share.

Performing Babyface is a constant oscillation between loving the way people admire me and hating the gaze through which they do so. I am a strong believer in the power of dance and choreography; so much of why I love dance and believe it's powerful has to do with how it's impressive. I lean into this heavily in the creation and performance of Babyface: the movement, and the frame that it's housed in, are an impressive spectacle. There is a magical (if glitchy) connection between breath and motion; there is a motivation in catching and enjoying the syncing of a beat; there are flowy, complex sequences of motion, moments when I kick my legs high into the air, moments when the wings expand with my breathing in such a way, and I think to myself, "I'm doing something nobody else could think of, and few are able to execute."

I'm deeply in tune with the structure that I'm wearing, and have a deeper awareness of the space immediately behind me. I can tell right away if something glitches or is wrong; I can feel the way the wings change the weight distribution on my back when they are extended or folded, I can hear and feel the vibration when the motor activates. I maintain a sense of control over how the wings move, as I am able to send my breath into the place where the sensor is situated. Familiarity and rehearsal have helped me understand the differences in how sensitive the sensor is in certain positions; for example, if my hands are high above my head, I need to make sure I'm sending breath deep into my ribcage, because when I lift my arms I have the tendency to puff out my chest and lessen the impact of my breath.

I'm especially aware of how much space I'm taking up, because it's more space than I usually do. I have a generalized sensitivity to this as a woman and a former ballerina; I'm rather trained not to be a nuisance, to not take up too much space, and to be highly aware of how I'm occupying it. As the cyborg, my relationship to these tendencies changes. I take up much more space and I am highly noticeable; but I am extremely attentive to the positioning of my body and the speed at which I take certain motions.

The wings themselves walk this fine line between immovable and fragile; I don't want to run into anything for fear of breaking the wings; however, the structure they are housed in limits motion through my upper back and shoulder girdle. This supports a more formal, upright posture, and distal motion in the hands and feet.

My experience of performing this work is sometimes so physically frustrating that the question, "do I need these wings" comes across my head. The answer: Yes. They have to be there. They have to move with me and separately from me, as a metaphor for expectation and control. They have to be ethereal and fragile and also a burdensome spectacle. They have to make me bigger, make me take up too much space, make visibly obvious the way I am often treated: as a pretty problem. They have to force me to manage space in this obnoxious way. And above all, the wings have to make me navigate the complicated relationship I've formed with them, so that people look at me and wonder what's real and if I'm human, and then fully, deeply understand that I am.

5.2 Participant Perspectives

Participants entered the installation in a state of wanting to be entertained. Either they had come to the Arcade with this intent specifically or the installation caught their eye as they were walking by (although the majority of participants were in the former category). Many had just watched one of the hourly performances, but some had only seen the performer improvising in the space. In either case, they typically entered with some giggly trepidation: stepping up into the space[2] that was often ringed by a collection of onlookers, they immediately recognized the experience of entering a performance area and being "onstage".

Wrapping the sensor around the body of the participant also created a degree of transformation and role playing that created an understandable sense of self-consciousness and of being watched. Participants with friends onlooking would often laugh or joke with their friends in this moment. Others would

[2]Note, for accessibility purposes, we could also trigger the wall from the sidewalk level, but we did not have any participants that needed to use that option.

look anxiously at the presenter and adjust their clothing nervously.

In both cases, during the "calibration", participants focused on the instructions of the docent, seemingly in order to not "mess up" or "fail" at the task. This afforded an immediate shift from an external, presentational, and interactive mode of action to an internal, somatic, and meditative mode, as the participant listened to the docent and worked to make their bellies move with their breath as described by the facilitator.

Almost all participants had at least one "ah-ha" moment in controlling the wall. In a very few cases, we offered the ability to press with the hand when breath was not sufficient to create a differentiated enough threshold through belly deformation. From these first moments, as participants began to move around the space, forgetting their breath or twisting into poses and movements that deviated from an upright neutral in which the calibration took place, the wall unit would often fire in less predictable moments, with a fair amount of user-to-user variability.

Once this "ah-ha" moment occurred, the docent offered a choice: to move about the space, exploring on their own and interacting with the performer, or to move along to a track that would guide them through choreography. About half would elect to perform the choreography, which situated them inside the same performative frame as the professional dancer and gave onlookers a new perspective to many of the same choreographic structures, now on the body of this bystander.

When the participant elected to "perform the choreography" the performer would typically join in, helping the participant resolve the movement commands featured in the voiceover. The initial few commands are quite easy to buy into, e.g., "Look into the mirror" and "Put your hands behind your head". Most participants followed these instructions with little vulnerability. But, then, when participants were asked to move their hips back-and-forth – as they faced away from the crowd – and the performer began a series of hip thrusts with a sexual, presentational tone – participants often began to feel embarrassed, silly, or even afraid. Some would even use physical strategies to tone down the protrusion of their hips from side-to-side.

Building from there, the audience, seeing the vulnerability and exposed nature of the participant role, was offered a new insight into the challenges of this cyborg character. What initially reads as a fun, disco-themed party becomes a creepy, awkward role to navigate. Thus, by the time the audience is, at the end of the experience, asked to "Clap for this beautiful angel" a range of reactions occurred. Some exuberantly joined in, laughing at their friend or companion as if they were attending a roast for the individual. Others felt uncomfortable at the request, worrying for the individual onstage. This awkwardness would be dissolved when the voiceover asked "Take a picture", engaging everyone in a familiar activity: pose for the picture and post! This is a call and response that often happens in social settings where gender is performed. The performative simulation creates an opportunity to realize our own participation as audience members in the presentation, celebration, and limitation of feminine gender in society more broadly.

Throughout the performance, the framing of the wings as wide and flat, the opportunity for self-inspection and reflection in the mirrored fragments of the wings, the setup of the shipping container as pseudo-stage, and the motion of the body as posed, linear, and frontal make the whole experience highly "Instagrammable." This ability and desire to be photographed becomes as an extension of seeking approval, likability and share-ability – a search for relevance via the archiving of self.

Indeed, the final prompt for viewers and participants alike is an invitation for the experience to be recorded: to take a picture of themselves augmented by an expressive machine that makes them, simultaneously, a magnificent and absurd spectacle. This photograph could be a point of pride: look at me, a part of this installation, in control, affecting this imposing structure with my own breath and motion. It could also be an embarrassing record of an uncomfortable, vulnerable, or objectifying experience. Regardless, this photograph adds to the existing archive of hundreds of millions of hyper-feminized images and photographs that fed the motion and material of this work to begin with.

5.3 Creative Perspective

Babyface is a work that seeks to meet audiences where they are. The motions, materials, structure, and interactive components of this work are meant to be familiar and immediately referential. We see a set of glittering wings on a wall, framing a hyper-femme cyborg barbie. We see our own image reflected back to us in mirrored elements that cast light around like a disassembled disco ball. We hear pop music beats and a feminine voice that reminds us of automated technology. We see poses that we've seen a hundred times before, on the bodies of "#cute" women on Instagram and across popular media.

Babyface is blunt with its spectacle as a pathway to its own subversion. An essential motivating question throughout our process was: how do we get audiences past the initial moment of, "oh my god, it's a robot on stage!" and therefore able to engage with our higher level concepts? Our answer was to fully embrace this moment. If we can first confront audiences with a familiar, predictable stereotype (robot barbie with segmented motion and a fixed smile), we can then reveal the shortcomings of that stereotype (the struggle against aesthetic restriction and the vulnerability that comes with being on display). Indeed, many viewers of this work referred to it as "accessible," noting the clarity of its narrative and immediacy of its references.

One feature of this accessibility is that kids found the installation really *fun*. While they are not our intended audience, it made the installation more popular, given that families could visit and enjoy with their children. To allow children, and many adults, to enjoy the work meant that some of our audience was missing out on the larger societal context and pointed critique embedded in the work.

In thinking about our adult audiences, "accessible" comes as its own kind of double-edged sword. Much in the same way that hyperbolic feminine performance can be viewed as cheap or simplistic, is "accessible," as a point of feedback some kind of code for facile? Perhaps we as creators would not feel this way if we were not also women working at this murky intersection of arts and technology; if instead audiences asked us how it worked rather than if we knew how it worked; if they weren't shocked when we said that we were designers, engineers, fabricators in addition to performers and choreographers.

We're sure these inquiries were not intended with malice, more likely with interest and curiosity. However, like an adorable, curvy service bot or a voice assistant that defaults feminine, the assumptions are still there: you are woman, therefore one can assume you are capable of this, or not capable of that. So we look back into the glittering wall, at the shards of ourselves, fix our smiles and inhale, our wings sliding out to frame our experience in their limited expanse.

6 DISCUSSION

This work alludes to broader principles that may apply to many robotics projects. Challenges around construction and design highlight distinct temporal cycles present in choreographing with live, intelligent bodies vs. building rigidly with units of programmed plastic. The need to express (and relative success of expressing) a particular meaning to audience members through both a passively-viewed performance and an actively-engaged experience highlights important context to consider when presenting robots. This section will highlight themes that may apply to future human-robot interaction and performing arts collaborations with different thematic aims and aesthetic textures.

• *Negotiating distinct design cycles.* Design thinking encourages iteration on many ideas, exploring the design space and improving intial ideas through refinement. A challenge when working with bespoke robotics in tandem with choreography is the distinct inertia of elements of the work. A piece of formed plastic, once manufactured, becomes a fixed design element. A piece of code is much more malleable but often takes significant debugging time to rework. A piece of movement can be adapted as late in the performance creation process as *onstage by a performer*. This can result in movement that befits the exact moment of a performance with a machine that looks extra or unneeded. Given the costs associated in creating the machine, this requires stringency in letting go of elements that are not needed. For example, we manufactured and carted over 100 additional plastic elements to New Zealand from the US that were unused. Instead, we spent our installation time refining the motion of the installed elements and the user experience in the container.

• *Accommodating the innate spectacle of robotic systems inside the established conventions of contemporary dance and performance art.* There is spectacle inherent in both robot and human bodies onstage. But, robots onstage have fewer precedent works and their novelty can get in the way of an authentic medium for expression. Moreover, robots are subject to wild hyperbole in their public presentations, including prior contemporary artists who have worked with the devices, portraying anthropomorphic devices augmented by theatrical and performative enhancements. In *Babyface*, we could not fully remove the spectacle of a woman controlling a robot onstage and instead leaned into that creating a character fueled by spectacle. The result was an inherent compromise between how the idea might have been communicated in a purely contemporary dance language of movement and how a utilitarian machine might be designed for efficient function.

• *Navigating being femme bodies who produce technically impressive work.* In the setting of the installation, audience members were often impressed with the scale and unseen functioning of the devices and their coordination with tightly performed movement vocabulary. This could elicit hyperbolic reactions that created two distractions from the main work. One, audience members may have been assigning more capability to the devices than they actually had. And, two, these reactions could prompt immediate questions that were often accompanied by an incredulity that was hard to navigate for the two petite female-presenting bodies presenting the work. For one, we worked hard to emphasize that the machine (led by our second author) would not exist without the artistic framework (led by our first author). Our goal was for the kind of collaboration where both engineering and arts skilled were valued equally. Indeed, the movement of the machine is a choreographic choice as well as an engineered design.

How these problems manifest in future work and other projects will always be different than how we encountered and handled them in *Babyface*. In fact, we leave this project with more questions than answers:

- *What is the correct balance in maintaining creative flexibility in machine and algorithm design so that the piece does not evolve beyond the machine, creating an unnecessary element?*
- *Where is the correct balance between explicating the inter-workings of the device and allowing for room for awe in the audience?*
- *How do we appropriately attribute the complexity of these collaborations?*

Striving for ways to accommodate design elements with various associated inertia and acknowledge the contribution of different kinds of knowledge is the only way to create novel human experiences with robots. Yet navigating two fields of distinct training and traditions requires some creativity and generosity on its own, separate from that required to create new work. In this spirit, these points and open questions present exciting avenues for future work, exploration, and experimentation.

7 CONCLUSION

Babyface, in its original kernel, was a short performance meant for a proscenium setting. This particular iteration of it took it out of a passive place and into an interactive space; in other words, what was once a performance meant for watching became a sculptural, robotic performance installation with multiple access points and channels for individual experience. It became a vehicle for novel play with emerging tools – for both performers and audiences. Situated in the artistic context created for *Babyface*, these tools become expressive and meaningful.

Further research into breath in the context of gender perfomativity, robotics, installation, and feminist studies will guide this project towards its next iteration. Future plans for this work include extending it into a stand-alone, evening length-experience, as well as fine tuning the interactive element. Technically speaking, the creators have plans for a multi-modal breath sensor, for both wearable and wall-mounted robotic structures. This would measure breath filling and emptying throughout the volume of the torso, accommodating nuances person-to-person in belly, breath, and chest breathing. Theatrically speaking, the creators would like to develop the interactive experience in a less open-ended setting, guiding audiences in a more controlled manner through the nuances of aesthetic awesomeness and physical limitation.

The work's essential ideas around the spectacle of woman and machine, the pressure of feminine presentation inside of screen based media, and the limited view of femininity spread by technology provided the basis for an extension of this work into an interactive performance – one that seeks to make the experience of hyper-feminine spectacle literal and re-livable for its audience. These ideas became design parameters, extending to the materials and the construction of the performance space through to the motion of the machines and the humans wearing them. In our case, in exploiting the spectacle of robots and theatrical femininity, our work became an impactful form of social commentary. This particular end was unique to our goals but highlights some of the crucial steps to building expressive machines. The end affective goals must be part of the design process from concept to implementation, requiring expertise from both human-robot interaction and the performing arts.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

KL and AL are co-first authors of this paper, writing in a collaborative balanced process. KL and AL both secured funding and resources for this project. KL led artistic development, choreography, music direction, and concept, and AL led technical development, mechanical design, algorithm and sensor development, and academic contribution. Both authors contributed to all of these areas along with additional team members listed in the Acknowledgments.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frobt.2021.576664/full#supplementary-material.

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OUTPUT: Choreographed and Reconfigured Human and Industrial Robot Bodies Across Artistic Modalities

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Millions of industrial robots are used across manufacturing and research applications worldwide. Handfuls of these robots have been used in dance, installation, and theatrical art works as tools and performers. *OUTPUT*, a collaborative artwork presented here, employs an industrial robot as choreographic source material and dancing body in order to reframe these robots as performers and bring them into closer proximity with the general public. This *OUTPUT* work has existed as a performance, installation, and augmented reality application. All three formats of the work include improvisational components, where a human can dance with a representation of themselves alongside an industrial robot, facilitating an embodied and creative experience next to these sequestered machines.

Keywords: robotic art, human-robot interaction, performance, improvisation, art installation, motion capture, dance

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INTRODUCTION

Several million industrial robots operate worldwide today (Heer, 2019). The majority of these robots are used in factories during the manufacturing of many types of products: from cars to consumer electronics. These robots are often inaccessible to the general public, however, because they are regularly large and heavy, at hundreds or thousands of pounds and reaching heights taller than human averages. This size means they are commonly bolted to a single position or track, and thus, cannot be easily removed and transported from their station. In addition, industrial robots are expensive, stiff, and customized to factory settings; they are frequently used for highly precise, repetitive tasks. Finally, they are inaccessible to the general public because in certain cases they do not have force/torque or contact sensors that would indicate whether the robot has hit something unexpectedly, like an obstacle or a person. Therefore, many people have never seen these robots in real life, and even more unlikely, up close.

Artists and researchers have explored how to make these sequestered robots accessible to the general public by incorporating them in artworks, demonstrations, and articles. Some of these artworks explore how industrial robot motion differs from human motion; others include custom software that controls industrial robots through movement (Apostolos, 1985; Byrne et al., 2014; Özen et al., 2017). These industrial robots have also been utilized as characters in plays and installations, in order to prompt imaginings of robot capability.

OUTPUT, an artwork created by a dancer and choreographer while in residence at a software engineering company, investigates how to make this unreachable robot presence tangible. The work employs an industrial robot and a human dancer as performers across different mediums - dance, film, and software - in a performance, an art installation, and an augmented reality application. The two primary themes of the work are: 1) Reframe an inaccessible and physically intimidating, yet commonly used, robot into choreographic source material and performance partner. 2) Allow the general public to not only watch but interact and take part in the work by facilitating closeness between humans and robots through many types of media. The work *OUTPUT* tackles questions about how human movements and robot movements become used and reconfigured over time/technology. The work invites the public to explore these questions from an embodied, visceral, choice-making point of view by providing them with improvisational tools.

This article positions *OUTPUT* in relationship to other performances and artworks involving industrial robots. It describes the technical and artistic mechanisms underlying the *OUTPUT* work and how the work extends prior artistic investigations. Following the Introduction, a Background section describes a brief history of industrial robots, prior influential works with industrial robots, and human-robot interaction in relationship to choreography. The Artistic Motivation and Choreographic Execution sections detail the artist's questions and the mechanics of choreographing the industrial robot. The novel software contributions are recounted in Software Programs. The next three sections: As Performance, As Installation, and As Augmented Reality Application, chronicle *OUTPUT* in each of these forms. Discussion frames within broader theoretical choreographic concepts, the aforementioned prior works, and the questions posed at the conception of the piece. Conclusion describes future directions for the work.

BACKGROUND

Industrial Robot History and Contemporary Context

The Unimate is often considered the first industrial robot arm (Moran, 2007). It was devised in 1959 by George Devol and Joseph Engelberger, two inventors who were deeply fascinated by Isaac Asimov's robot stories from the early 1940s. The Unimate's first successful application was as an assembly line robot at the General Motors diecasting plant (Gasparetto and Scalera, 2019). Several industrial robot arms followed as mass manufacturing increased across Japan, Scandinavia, Eastern Europe, and the United States. The Stanford arm was developed by Victor Scheinman in 1969 (Scheinman, 1969), and learnings from this robot informed the design of his PUMA robot arm, an acronym for Programmable Universal Machine for Assembly, built with collaborators at GM and introduced in 1978 (Beecher, 1979). In that decade, new companies came into existence including KUKA, Nachi, Fanuc, Yaskawa, and ASEA; estimates at the time noted a new robotics company was created every month (Conditt, 2011). Since then, industrial robots have expanded across manufacturing applications like welding, packaging, and assembly of items like cars, lumber, and food. According to the International Federation of Robotics (IFR), there are between 2.5 and 3.5 million industrial robots in use today (Heer, 2019). By revenue, ABB Group is the largest creator of industrial robots (Chakravarty, 2019).

Some social or research robots, like SoftBank Robotics' Pepper, Rethink Robotics' Baxter, or KUKA's iiwa, have cameras, collision sensors, and robust readings from force/torque sensors to determine if the robot has made inadvertent contact, causing the robot to slow or stop moving (in some applications, this is also known as active compliance (Fitzgerald, 2013; Pandey and Gelin, 2018). Several historic and contemporary industrial robots are not equipped with such sensors or algorithms to confirm if they have come into contact with their environment as their use does not require contact awareness (Conditt, 2011; Siciliano and Khatib, 2016). This renders industrial robots dangerous for humans in close proximity. As a result, industrial robots are caged or housed in structured, standalone environments away from people. Thus, interactions between humans and these industrial robots are often not directly physical, but rather computational (by programming robot tasks), theoretical (considering other features of the robot, such as its economic, historical, or creative meaning), or through a barrier. An interaction might be fully closed loop or open loop in varying degrees of abstraction.

Discussions about the future of work often include various forms of automation, including industrial robots. These robots are both (human) labor-augmenting and labor-substituting. In a 2017 European Commission study, 72 percent of Europeans believed that robots and artificial intelligence "steal peoples' jobs." However, analysis of human employment and robot deployment in Europe does not clearly indicate whether these variables are negatively or positively correlated (Bessen et al., 2020). Analysis on the US Labor Market from 1990 to 2014 indicated that industrial robots had negative effects on employment in localized communities, even though national job figures improved (Acemoglu and Restrepo, 2020). It is not clear whether the actual trend *or the discourse* surrounding contemporary automation is a historical aberration, as one count demonstrates that the majority of today's jobs did not exist 50 years ago (Atkinson and Wu, 2017; Benanav, 2020). Studies about many types of robots indicate that people who are less familiar with the robotic technology are more likely to fear their impact on employment (McClure, 2018). One analysis argues that humans have a history of projecting their extant fears into fictional representations of robots, which differ significantly from today's actual robots in research labs and companies (Szollosy, 2017).

Industrial Robots in the Arts

Creative investigations at the intersection of robotics and various artistic mediums are frequent. Jochum, Millar, and Nuñez drew inspiration from puppetry to formulate strategies for robot motion and design (Jochum et al., 2017). Knight and Gray (Knight and Gray, 2012) drew inspiration from acting, and LaViers, Cuan, Maguire, et al. from dance (LaViers et al., 2018). Researchers also employed the theories of New Animism and its performative technique called "mimesis" to elucidate differences between robot and human entities as a design tool towards building non-anthropomorphic robots (Dörrenbächer et al., 2020).

Decades before the research and artistic works above, in the 1960s, Scheinman collaborated with then Biomedical Engineering PhD student Larry Leifer to create his Stanford industrial robot arm. Leifer became a Professor of Mechanical Engineering at Stanford years after. In the 1980s, dancer Margo Apostolos studied at Stanford for her PhD in physical education and collaborated with Professor Leifer on a series of robot-only ballets, StarDance (1983) and FreeFlight (1984) (Apostolos, 1985). Apostolos began working with Leifer after auditing his course and inquiring why factory robots did not move more gracefully (Williams, 2017). Apostolos also created dances with the Spine industrial robot alongside human dancers in the early 1980s. (Apostolos, 1988).

Prior works with industrial robots led to the formulation of new tools for artists to program robots. Bot & Dolly, a design and engineering studio, buildt software and hardware so artists without robotics experience could interact with industrial robots during the making of films and installations (Byrne et al., 2014). Özen, Tükel, and Dimirovski wrote the program LabanRobot to automatically translate Labanotation into movement for the Mitsubishi RV-7FL (Özen et al., 2017). Researchers engineered an improvising robotic musical instrument that responded to the gestures and sequences played by a human (Hoffman and Weinberg, 2010).

Recording and representing human movement is an ongoing challenge. Choreographers, researchers, and engineers alike have employed notation (such as Labanotation, Eshkol-Wachmann Notation, and Action Stroke Notation (Eshkol et al., 1970; Hutchinson et al., 1977; Badler and Smoliar, 1979; Cooper, 1997) and abstraction (such as stick figures or animations (Marr and Nishihara, 1978; Badler and Smoliar, 1979) to capture and demonstrate motion sequences. Human movement has been utilized as source material for humanoid robots with differing kinematic structures via mappings (Do et al., 2008) and deep learning techniques (Aberman et al., 2020). Industrial robots have appeared in live performances and installations. Two industrial robots appeared with a human actor in the play Fremtiden (The Future), controlled by offstage human operators. Snyder, Johns, Kogan, Avid, and Kilian utilized an industrial robot as a musician during a live performance including projection mapping (Snyder et al., 2015).

Situating *OUTPUT* Relative to Other Performances and Artworks

To contextualize the *OUTPUT* work, this article includes a detailed discussion of a small number of performance and installation works created with industrial robots. In addition to utilizing an industrial robot in a primarily non-verbal work, these artworks share a few additional themes that will be further addressed in the *OUTPUT* work through the Artistic Motivations section:

- Robot bodies human bodies. As noted, the effect of robot labor is largely hidden inside factories or by the forward passage of time. These prior in closer proximity works, as *OUTPUT* does, attempt to make that robot action known by bringing the robot to the general public.
- Humans as robot creators as well as robot "responders." The artists utilize the robot as a tool for expression in the making of these works, by modulating the robot's behavior or movement, and consequently react to that formulated action.

The industrial robots used in these pieces and *OUTPUT* are serial manipulators, meaning one joint is attached in series to a single next joint. This joint can be revolute (revolving around a single axis, like the center point of a clock hand) or prismatic (sliding linearly, like a bead along a string). The last joint of a serial manipulator robot is frequently equipped with a tool or attachment, known as the "end effector" (Siciliano and Khatib, 2016).

In *PROPEL*, Stelarc attached himself to the end effector of an ABB IRB 6640 via a metal bracket and straps in order to feel an intimate connection between himself and the robot. The robot performed a choreographed motion sequence, and due to their physical connection, the robot's motion dictated Stelarc's overall trajectory, velocity, position, and orientation in space. The robot's sphere of motion is constrained by its size, as it was bolted to the floor. The robot's motors provided the soundtrack. This piece demonstrates an instance of scripting robot motion in order to affect human motion. Stelarc is "stationary" throughout the piece, in that he does not move his own limbs, but is instead directed through space by his attachment to the machine, an instance of human-robot physical coupling. If the robot were to collide with another object while Stelarc was attached, both the robot and Stelarc would be injured. Stelarc relies upon the chosen choreography and the consistency of the robot's motion in order to guarantee his own safety.

Stelarc's prior 1995 work, *Ping Body*, is thematically similar. In this piece, he attached a muscle-stimulation system to his right arm and allowed remote audience members to actuate it through their Internet domains. The distance and density of random pinging between these domains and his performance website were mapped to voltages on the stimulation system, forcing Stelarc's arm to move. This piece demonstrates chaos in both a natural and machine system embodied in one entity - Stelarc retained control over his limbs, head, and torso while allowing the dictation of his right arm (Shanken, 2009; Stelarc, 2009).

In *Black Flags*, Forsythe considered the question "What types of gestures can a robot body perform that a human body cannot?". He utilized two KUKA industrial robot arms to wave black flags from their end effectors during a 28 min performance. The stationary robots are constrained by their link lengths and confined to a scripted motion. The distributed weight of the flags is prohibitively high for most humans to carry. Forsythe made modifications to the robot's motion based on the environment when it was reinstalled (Forsythe, 2014; Elkin, 2017). *Black Flags* is not a participatory installation or performance in the same manner as *PROPEL*. It uses a subtler form of robot bodies affecting human bodies as the waving flags create gusts of air that can be felt on the observers' bodies. In addition, it demonstrates how gestures many be natively generated based on the physical capabilities of the moving body. Once it is scripted, the robot performance does not change each time it is performed. The work is thus shown live to a group of viewers, but is not reactive to the environment or the other robot performer in the pair. Motion consistency is core to the perception of the work.

Huang Yi and KUKA is a choreographed dance between several human dancers and a KUKA industrial robot arm. Yi choreographed the robot and also performs in the piece. The robot is affixed with a laser beam in different colors at the end effector, a tactic that creates literal boundaries of space on stage (Kourlas, 2015; Lin, 2016). The scripted robot interacts with Yi in that his movement was initially generated to be a duet with the robot's. He also physically contacts the robot during their opening duet. Thus, Yi's interactions with the robot are choreographic and physical. Yi's movements towards and away from the robot, coupled with his mirroring of the robot's motions, appear as a shy introduction or manifestation of loneliness. This emotional relationship to the robot paints it as a character. In the closing section, the two dancers' movements are seemingly dictated by the shifting robot's moving laser. This evidences the idea of a robot body affecting a human body, now from a physical as well as emotional point of view.

Mimus is an installation work with an ABB IRB 6700 robot, also named Mimus by the artist (Gannon, 2017). Eight depth sensors on the ceiling capture the viewers' moving bodies and software assigns explicit and implicit attributes to them, like age and "engagement level." The robot reaches towards the "most interesting person" based on those criterion. The robot's movement is dictated by the commands from the sensing software and a set of behaviors that exude animal behaviors. The robot is stationary on the floor and contained in a glass box (DesignMuseum, 2016; Gannon, 2016). This installation closes the affect loop, in that the robot's actions affect the installation viewer's reactions and the installation viewer's motion influences the robot's behavior. The encoding of animal-like behaviors again lends character to the robot. While the behaviors are scripted, the sequencing of them is determined by the overall system and therefore unknown in advance.

ARTISTIC MOTIVATION

The directors of the ThoughtWorks Arts residency held an open call for artists under the title, "Mechanical and Movement," in spring, 2018. The Consortium for Research and Robotics (CRR), a Pratt-affiliated research institution housed at the Brooklyn Navy Yard, uses two industrial robots for research into materials science, architecture, and human-robot interaction. ThoughtWorks Arts partnered with CRR for this residency and later worked with Red Frog Digital Limited on an overall ThoughtWorks Arts augmented reality application.

OUTPUT was created during an initial 12 weeks residency period at ThoughtWorks Arts in New York City over summer, 2018 (Cuan et al., 2019; Cuan, 2020). Additional elements of the work were modified and introduced in fall, 2018, and summer, 2020. The collaborative team included the resident artist (dancer and choreographer Catie Cuan), ThoughtWorks software engineers (Andy Allen, Felix Changoo), ThoughtWorks Arts director Andy McWilliams, CRR roboticists (Gina Nikbin, Noor Saab, Cole Belmont), creative coder Jason Levine, Red Frog Chief Technology Officer Alessandro Mondaini, and ThoughtWorks filmmaker Kevin Barry, with additional creative advising from ThoughtWorks Arts director Ellen Pearlman and CRR director Mark Parsons.

Initial meetings across this collaborative group probed questions of agency and partnership between humans and robots. Cuan identified a central theme of "movement presevation," or how motions are taught by people to other moving human dancers and translated into directions for robots. The ways in which that motion is altered, glitched, and reformulated became thematic palettes for the work, presenting the questions - what is pure movement? Can aesthetic value be drawn from the records and interpretations of movement rather than the pure, originating movement itself? How do performers, when interacting with their own movement on new bodies at a later time period, own or interpret that motion? How do movement themes, when layered and synchronized across these representations, create a visual group piece, similar to instruments in an orchestra playing in a symphony?

The collaborative team decided to use the ABB IRB 6700 robot named "Wen," a 10.5 foot high industrial robot located at CRR, as it was a primary example of an inaccessible robot. This Wen robot primarily effects objects and environments through motion and contact (vs. a chat bot that generates readable text). This characteristic makes the robot both a choreographic resource and a viable performer of dance. This robot is used by the team at CRR for materials research and prototyping. The hard materiality of the robot removes it from the realm of science fiction and places it strictly in the present space and moment. Thus a secondary theme emerged of using the robot's movement quality, appearance, and economic status as choreographic source material. What types of motions does this robot perform in those hard manufacturing scenarios? In what way does changing the context of the presentation of the robot render it as a skilled performer rather than a tool for economic production? Does it alter our impression of repetitive machine motion and perhaps highlight how we ourselves repeat certain motions in order to conform to the machine interfaces around us?

This robot's enormity and speed renders it hazardous for humans in close proximity similar to other industrial robots described in the Background. This robot is also fixed to its location in the Navy Yard. This absence of tangible physical interaction and mobility led the artistic team to consider other forms of interaction and transportation, a challenge that supported and further extended the theme of recording and reconfiguring motion across distance and body representation.

CHOREOGRAPHIC EXECUTION

Choreographing motion for non-humanoid robots is a challenge extant in the aforementioned works and explored in *OUTPUT*. In order to create *OUTPUT*, the roboticists at CRR shared initial details with the collaborative team about how to program the Wen. Two programming options were possible: selecting a continuous trajectory for the end effector or selecting joint velocities for each separate joint (one at a time, or coupled together). Both of these options force a distinctive choreographic process subject to temporal linearity, meaning a beginning and an end are enforced by each of these programming models. Altering motions once a movement sequence is generated, such as inserting new motions or modifying existing ones, became arduous as the robot's configuration may result in a singularity, an unsolvable set of joint parameters that cause the robot to stop moving.

Cuan developed a choreographic process where she mapped the robots joints onto select limbs or her entire body. For example, the robot's end effector might be her head in a full body mapping, or the robot's end effector may be her hand, in a right arm only mapping. She then created a human dance sequence inspired by the notions of physical labor (watching recordings of the robot moving in a manufacturing context and live at CRR), repetition (as the robot's motion is frequently repeated during these other manufacturing use cases), and ordered sequencing (for example, the robot's joints were numbered 1 through 7 in bottom to top order, so runs of joint motions in order might be "2, 3, 4" or "1, 2, 3, 4, 5"). After she created this human dance sequence, she selected when to use full body or isolated mappings on the Wen robot and which joint programming may be suitable for either mapping. Cuan observed the robot performing the sequence and made additions to her own choreography, creating an interactive feedback loop between human and robot body for motion generation. The process of choreographing a 5 min motion sequence onto the robot took approximately 32 h of work at CRR, not including the artist's time spent generating choreography in advance and between work sessions.

The two long motion sequences for human and robot differed on a few dimensions. The human sequence included tempo variability, specific eye gaze points, and broader spatial exploration. The robot was confined to a narrower velocity band and moved along one line, forwards and backwards. At this point, the two long motion sequences for human and robot as well as a generalized mapping process were performance components. The central artistic theme of recording and reinterpreting these sequences across sensing technologies lay ahead. ThoughtWorks engineers Andy McWilliams, Andy Allen, and Felix Changoo extracted the Wen's joint angle data over the full 5 min sequence and used the angles to populate a moving animation of the robot. Thus, two layers of motion recording and transference existed within the robot animation itself: from Cuan's original choreography, to the robot's motions, and finally the resulting joint angles. Cuan and filmmaker Kevin Barry captured footage of the robot moving alongside Cuan's original performed choreography at the Brooklyn Navy Yard CRR loft, seen in **Figure 1**. Real time regeneration and repurposing of the animation, robot video footage, human video footage, and human dance would be handled by two new pieces of software and two cameras.

SOFTWARE PROGRAMS

Two custom pieces of software were written for *OUTPUT*: CONCAT and MOSAIC.

The artist desired the ability to perform the original human choreography next to the translated robot choreography in order to demonstrate the glitches, alterations, and aesthetics of each. For example, a glitch in human choreography might be when the performer loses balance and needs to add an extra step in the sequence. The Wen robot makes no such errors when doing the finished sequence. The human choreography lifts off the floor during jumps, but this trajectory must be altered for the Wen as it is bolted to a track. Given that the robot animation contained two layers of recording translation, while the robot film was one, Cuan also endeavored to show *herself* dancing in layered translation next to these elements. CONCAT was programmed as a result. CONCAT is software built in openFrameworks, a C++ based creative coding platform, that placed a real-time human skeleton captured by a Microsoft Kinect v2 depth sensor next to the 3D animation of the Wen robot. A person oriented towards a laptop or projected screen of CONCAT could see their own skeleton and then, by moving around, observe their captured skeleton interacting with the robot animation through the screen. The Kinect depth sensor's limited range of capture constrained the interacting person to a particular area. The moving limbs of the robot animation and the captured human skeleton change color according to the fastest moving limb - inherently, in the case of the animation, and dynamically, in the case of the human skeleton. The primary purpose of CONCAT is to allow the participant to try on the robot's motion.

The inspiration for MOSAIC came from the performer's initial improvisations with the CONCAT software. Cuan recognized a desire to demonstrate the translation of pure movement across bodies and time in a multiplicative way, such that the prior motions could be contextualized with the real time ones. She envisioned the ability to play multiple instruments in an orchestra simultaneously, similar to a loop pedal or computer music interface, but for dancing bodies. The artist imagined this would secondarily support the question of repetitious motions in a manufacturing context - while a robot in a factory captured over a single time interval might always perform the same motion (i.e. a weld at the same location on a car chassis as the car passes through a factory line every 30 s), the insertion of a real time composer/improviser/conductor like the artist meant select layers and snippets could be arranged into a compelling overall landscape of motion. Cuan began to see this machine labor as possessing meditative continuity rather than monotony and sought to illuminate this reframing of machine labor. In addition, she believed the overall landscape may act as a mirror to the repetitious motions we go through in our own lives, often enforced by technology (typing, door opening, etc.).

MOSAIC is a software built in openFrameworks that stiches together up to 16 moving videos captured from a laptop webcam or external camera source into a single grid/collage. The duration of each individual video is based on a key command from the artist, and the content of each individual video repeats inside its

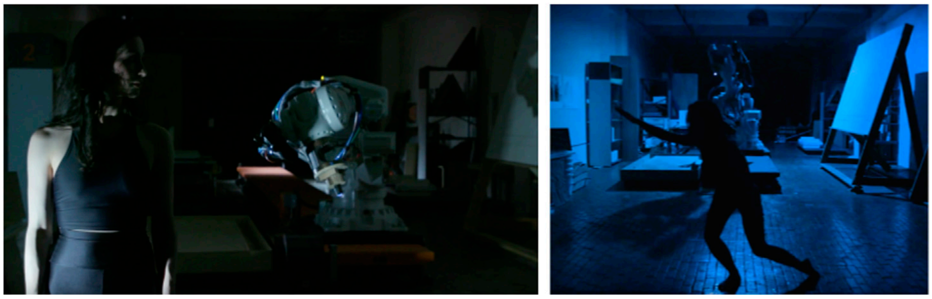

FIGURE 1 | Still images from the *OUTPUT* film. At left, Cuan stands alongside the Wen robot as flood lights illuminate them both. At right, the only light is positioned over the robot, obscuring Cuan's overall appearance and contrasting obvious elements of the robot and the human - such as number of limbs, joints, and size. Images by Kevin Barry.

FIGURE 2 | A still image from the MOSAIC software as utilized in rehearsal. The artist began to experiment with proximity in order to exaggerate her features to the scale of the robot's. Image by Catie Cuan.

rectangle unless it is removed. A person using the software can add or subtract videos from the collage in order to create a visual quilt of moving bodies. In doing so, the performer can dance with themselves or any other captured bodies in the camera view. MOSAIC additionally allows the artist to alter the size of the moving bodies (via proximity to the camera), supposed physical interaction between the human and the robot (via specific overlapped staging and gestures), number of overall performers (by adding more videos), and audience perspective (by situating the camera at any point on the stage). The orientation of the videos gives the illusion that the bodies are interacting with and affecting each other - for example, a video of the robot moving left to right along an upper left corner square may seem to "bump" the performer if a video Cuan captures on stage where she moves from left to right in the video next to it is timed at the exact right interval. The artist experimented with the MOSAIC tool during rehearsal, as demonstrated in **Figure 2**.

AS PERFORMANCE

Over the course of the *OUTPUT* project development, the artist noticed repetitious feelings of being "inside the machine," as if her own body had become extended into these different devices and

FIGURE 3 | CONCAT and MOSAIC seen during the performance premiere at Triskelion Arts. Cuan uses a wireless mouse to control MOSAIC and orients the web cam in order to capture the projection visuals from both CONCAT and MOSAIC simultaneously to feed into MOSAIC (top). Cuan dances in front of the Kinect depth sensor, populating the human skeleton next to the robot animation on the projector upstage with CONCAT (lower left). The performer constructs a collage of short, captured stage videos with MOSAIC (lower right). Images by Kevin Barry.

other moving bodies. She acutely noticed this when observing the Wen moving through the choreographed sequence for the second time at the CRR loft. During this regurgitation, she felt like her gaze had been transferred into the robot's end effector and she could see what the robot was "seeing": details on the ceiling as it tilted upward, the robot's own arm "elbow" as it rotated, Cuan standing in the Navy Yard studio at one end of the track. Without meaning to, she began marking through the robot's choreography herself, twisting an ankle or a shoulder as she watched the Wen, as if those robot and human joints were interconnected and the space between herself and the robot"s body had collapsed.

This sensation stretched the initial artistic theme of "pure movement" into one where simultaneous agency and presence is exhibited across recordings and bodies. The capability of the *devices* is de-emphasized while the human body's capacity for reverberation across modalities of space and time is foregrounded instead. From a choreographer's perspective, the kernel of humanness - as recognized through shape, proportion, gestural emphasis, and sentimental affect - seemed to proliferate throughout these representations. The symphonic layering, described in this initial artistic theme, could be one of controlled, dictated multiplicity, rather than a byproduct of recording over time. She felt the need to make this explicit in a live performance. Mark Johnson argued that we make meaning out of our thoughts through "a matter of relations and connections grounded in bodily organism-environment coupling," that sensorimotor activity may be a sort of objective truth for meaning (Johnson, 2008). Cuan's sensory responses to watching the robot and the representations of herself support the notion that meaning generation and comprehension are visceral, perhaps even moreso with a novel environmental object.

Thus, the artist's aims for a live performance were to generate improvised visual collages of the recorded and live moving bodies in order to illuminate the shared qualities and unique textures of each. She decided to bookend these visual collages with standalone original human dance solos and video of the moving robot performing the "same" sequence in order to highlight each body separately. Cuan was the solo dancer. Both softwares ran live time during the performance on two different laptops, with CONCAT connected to a Kinect and MOSAIC connected to a wired webcam on a 25 foot tether, seen in **Figure 3**.

Two projectors with screens upstage showed the CONCAT software (with the robot animation and human skeleton) in **Figure 3** and the MOSAIC software (as stiched together live

FIGURE 4 | The initial installation showing of *OUTPUT* at Pioneer Works in Brooklyn, New York, in April, 2019 (upper left). MOSAIC and CONCAT run live on two laptops while participants move in front of both the Kinect sensor for CONCAT and webcam for MOSAIC. CONCAT shown as a standalone installation at TED Education Weekend in New York City in February, 2020 (upper right), and at Critical Practices Unit at Stanford University in Palo Alto, in October, 2019 (lower right). MOSAIC shown as a standalone installation at the Dance/USA Conference in Cleveland, Ohio, in June, 2019 (lower left). Images by Catie Cuan and Cameron Scoggins. Used with permission from the participants.

time on the tethered webcam) in **Figure 3**. A wireless keyboard and wireless mouse allowed Cuan to control the MOSAIC software from anywhere on the stage. The webcam on a long tether let her capture her physically present self, the projected animations of the robot and her skeleton in CONCAT, and the projected recorded videos in MOSAIC. This effectively documents what the audience sees on stage during the performance, but from many more proximal and directional angles. The Wen robot could not be transported to the performing space so video of the real robot was shown on a large projected screen. This video footage demonstrates the robot's scale and original execution of the choreography.

Cuan employed an improvisational modality where she decided how to engage with each software - such as entering the space where the Kinect sensor captured her skeleton with CONCAT, or reorienting the webcam and adding or subtracting videos from the MOSAIC software - over a timed interval between the human dancing solo at the beginning and the standalone robot video at the end. In doing so, Cuan composed live, unique visual collages which conveyed similarities and differences across the live human body, robot animation, and robot film on stage. This practice is akin to live coding, an algorave, or solo dance improvisation. The capture and replay potential does not limit the solo dance improvisation to one body at one time (An algorave is an event where musicians code algorithms in real time on laptops running sound applications, thus producing improvised electronic music. The laptop screen is often projected onto a wall for the audience to observe the programming at the same time as dancing to the music (Collins and McLean, 2014)).

The overall performance lasts between 13 and 15 min and is performed to a single long track of music by artist Bonobo. The mood of the piece is dreamlike, oscillating between wandering and hypnotic, echoing the continuity of dozens of industrial robots bolted along an assembly line. The lighting is used to outline boundaries on stage where the performer will be in front of either of the two cameras - in a recording eligible zone. The performer wears a fleshtoned, closefitting garment to mimic the

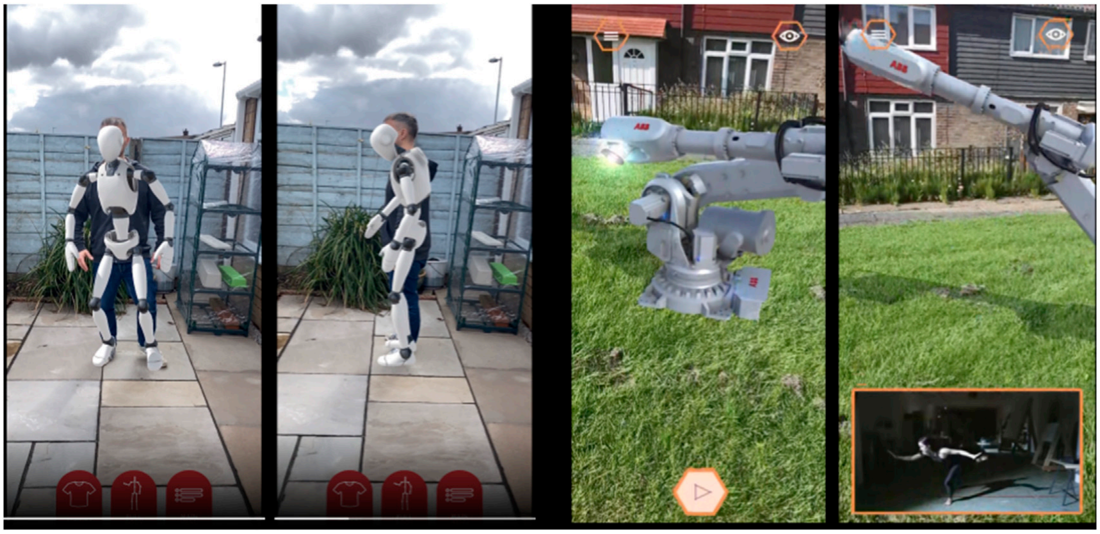

FIGURE 5 | Screenshots from the augmented reality (AR) application in progress. App users can see the ABB robot in 3D through their smartphone camera and the app. The AR robot rotates through poses from the choreographed sequence in the original performance. A video of Cuan dancing alongside the robot appears in an orange overlay on click. The app users can then "Try it yourself" and move in front of the smartphone camera while an overlay resembling a robot follows along their captured motion. Image by Alessandro Mondaini. Used with permission from the participant.

monochrome of the actual robot body as well as the captured animation and human skeleton (when they are not moving, each animation is completely red).

AS INSTALLATION

The artist's experience choreographing movement for herself and the robot during the making of the work, as well as the feelings of agency and bodily extension into new machines, were sensations she believed stood in contrast to the threatening or fatalistic impressions people often have of fictional robots. In addition, *OUTPUT* in performance provided a rich opportunity for Cuan to see her moving body redesigned by various sensors and algorithms. She was inspired to improvise with these replications because the replications seemed aesthetically and capably different from her own body. Presenting MOSAIC and CONCAT as interactive tools in an installation would allow other individuals to see their own bodies reimagined through various sensing technologies and to personally interact with the Wen robot in a kinesthetic, open-ended manner.

CONCAT and MOSAIC require minimal hardware, only laptops, a Kinect, a webcam, a projector, a screen, and a mouse. CONCAT and MOSAIC have been shown separately and together at five events, totaling approximately 300 participants, across one year. Installation participants have varied in age from toddlers to adults in their 70s. The artist was present at all events and would provide a basic informational script about the software or softwares that comprised the installation. Both tools were demonstrated for the first time as an installation in spring, 2019, pictured in **Figure 4**. The artist sectioned off a large floor space where the Kinect sensor would detect present bodies. She situated a laptop and a projector around this space, so participants could see their skeleton in one small laptop screen and capture videos of themselves on the second laptop screen. The projector showed CONCAT simultaneously, so passers by could watch someone participating inside the installation and then join themselves. The Wen robot could not be transported from the Navy Yard, thus the scale and size of the robot was diminished in CONCAT. The artist addressed this differential in two ways: by running CONCAT on a large projection screen to make the size of the robot animation as large as possible, and by bringing printed poster-sized photographs of the robot in the CRR loft alongside the choreographer to provide a sense of human-to-robot scale.

Over this yearlong period, participants often shared their verbal reactions with the artist. These installations were not formal experiments, therefore audience reactions were captured through informal artist reflections after the event. When CONCAT was shown, common themes include the surprise at the robot's small number of joints, curiosity about the appearance of their skeleton in the Kinect representation, and desire to see the "real robot" in person. When interacting with the robot animation through CONCAT, participants would mirror the robot, copy it, try to bump/affect it, and stretch the bounds of their own movement to occupy the entire captured screen. Participants express perceived challenges when trying to mirror or orient themselves in relation to the robot animation in the CONCAT, they ascribed this challenge to the simplicity of the robot or the divergent form factor from their duality (two arms vs. the robot's single arm, for example). Cuan noticed that CONCAT became a tool for individuals to perform motions that they may not investigate on a regular basis. In doing so, the Wen robot - and by extension the Wen animation - became choreographic source material *for the participants* and the theme of robot motion affecting human motion (as in *PROPEL, Mimus*) was extant in this interaction. CONCAT allows participants to map their own degrees of freedom onto that of the Wen robot's, posing the question of how their movement is impacted by the vision of a moving industrial robot alongside as well as trying on the Wen's movement profile. Thus, participants receive kinesthetic insight into the difficulty Cuan faced when formulating motion for a non-anthropromorphic robot. Two showings of CONCAT as installation can be seen in **Figures 4**.

When MOSAIC was presented as part of the installation, participants expressed detailed observations about their own motion as they viewed squares inside the collage. They also noticed patterns across each square and often generated several collages as they became more familiar with MOSAIC. In instances where they could include the robot animation in the MOSAIC collage, participants frequently captured their skeleton alongside, populating the full collages with not only several squares of video, but all the body representations they could. MOSAIC as a standalone installation has only been shown on one occasion, pictured in **Figure 4**. When presented individually, CONCAT emphasizes questions of exploratory embodiment and movement influence while MOSAIC underscores recording, repetition, and representation. When presented together, the improvisational and composition aspects of the *OUTPUT* work are reinforced, as the participant is both performer and visual creator of their experience with the Wen robot.

In general, either CONCAT, MOSAIC, or both have been presented in installation form at an adaptable, short term setting, without detailed attention paid to the lighting or exact configuration of the tools. For example, on one occasion CONCAT was shown next to a series of digital musical instruments and at another next to a robotic glove. This removes *OUTPUT* from the realm of performance and somewhat from the realm of installation. An alternative might be similarities to demonstrations or the utilitarianism of a machine on a factory floor. This artistic informality may have led participants to interact more or less freely with the software, or encounter the software's capabilities with more or less consideration to aesthetics or underlying artistic motivation.

AS AUGMENTED REALITY APPLICATION

The *OUTPUT* installation experience was extended by introducing another modality - an augmented reality (AR) smartphone application. This application invites individuals to learn about the original *OUTPUT* motivation and artwork and then "Try it yourself." In the informational section, individuals see a 3D AR rendering of the Wen robot and a video of Cuan dancing alongside, similar to the original performance where the dancer's and robot's unaltered bodies were presented at either end of the piece. This information priming about the work parallels Cuan's spoken introduction at the installation occurrences.

In the "Try it yourself" portion, one individual (the "dancer") stands with their full body visible to the phone camera and a second individual (the "audience") films them. The application overlays an animated robot, similar to the robot animation in CONCAT, on top of the dancer's moving body for the audience member to observe as pictured in **Figure 5**. As the "dancer" moves, their motion triggers changes in the appearance of the robot overlay (such as color and texture, similar to their captured skeleton in CONCAT), thus inviting them to explore their full range of motion and recognize how their phone's recording device alters the manifestation of their motion. The "audience" watches these overlay changes in real time, while the "dancer" sees them only during the recording replay. The "dancer" is moving only with the humanoid overlay, rather than the industrial robot, though they can toggle between the Wen robot AR animation and the "Try it yourself" section inside the app.

An option to send their work to the artist appears in the "Try it yourself" section. The works sent to the artist from the application will become elemental moving bodies in future *OUTPUT* performances. This participation practice echoes *Ping Body*, as the full performance system will be altered by the participation of geographically distant application users. In addition, this creates another opportunity for an interactive choreographic loop, where individuals are inspired by the theoretical concepts underpinning the *OUTPUT* work, then record themselves with the robot overlay to be observed by the artist, who will in turn generate new choreography for Wen robot to be incorporated into the next *OUTPUT* performance. This interaction with several individuals across capture modalities and performing bodies is a further reflection of the overall *OUTPUT* artistic motivation.

DISCUSSION

OUTPUT as performance, installation, and augmented reality application investigates two primary artistic motivations: 1) understanding pure movement and technologically-facilitated movement translation, as well as 2) repetitious or industrial objects and movements reframed into a performance context. During the making of the work, the artist recognized additional sentiments of extending into novel machines and how an embodied improvisation alongside these hidden yet ubiquitous robots might encourage individual conclusions about robots. These sentiments arose throughout the collaborative process and led to two original contributions of the work: 1) making a sequestered robot's physical presence tangible, felt, and known; 2) allowing the public to experience this presence through a variety of improvisational and compositional tools which give them agency to investigate the contrasts between these bodies and their movement profiles again, extending into these novel machines.

Each of the four highlighted prior works as well as *OUTPUT* fall within Lycouris' "expanded definition of choreography." Lycouris further described choreography as a practice in which "relationships between all the heterogeneous components of the work can be defined in a coherent manner (Lycouris, 2009)." Each work described in this article includes robots among the "components." In Stelarc's *PROPEL*, the "relationship" between the human and robot components is defined mechanically, Forsythe's *Black Flags* employs a similar mechanical relationship between the flags and the robots. Gannon's *Mimus*, Huang Yi's

Huang Yi and KUKA, and Cuan's *OUTPUT* define relationship with the robot through scripted motion and responsive behaviors, creating a social, causal relationship between the bodies in the performance/installation. The collection of these relationships and the resulting action between them forms a "compositional meta-system (Lycouris, 2009)." As such, choreography is not only a practice that results in dance, but one that denotes a set of constraints under which motion and action can occur. This necessitates discussion of two further critical concepts: Forsythe's "Choreographic Object" and Robertson, Lycouris, and Johnson's approach to "complex systems."

Forsythe addressed the notion of pure movement in describing his work "Choreographic Objects." He noted, "But is it possible for choreography to generate autonomous expressions of its principles, a choreographic object, without the body?. . .A choreographic object is not a substitute for the body, but rather an alternative site for the understanding of potential instigation and organization of action to reside (Spier, 2011)." In all of the aforementioned works, one "alternative site" was a robot body. The scope of the "action" for the robot body varied among the works: Forsythe and Stelarc were primarily interested in dictating the end effector of the robot due to the attachment of the flag/person, whereas Gannon and Yi dictated action for all joints on the whole robot body.

The *OUTPUT* artist changed her interpretation of pure movement at the conclusion of the work. She came to believe that movements or sequences of movements rarely, if ever, have clear origins - does it begin with the idea of the motion? Or when the motion is first done by a body? Or when the inspiration for that motion was first encoded as a vague memory? - and even less clear conclusions - is the motion over when it is performed? Or seen? If it is saved indefinitely in a recording, does the motion ever end? This led her to believe that pure motion has translational and perceptual components - a pure movement is anything which can be recorded and transposed into another body or representation and therefore must be sensed - either by another human or a tool. This conclusion aligns with Forsythe's assessment that "choreographic objects" can alter the traditionally temporary status of choreography on human bodies, and instead facilitate the existence of a choreographic idea in "another durable, intelligent state (Spier, 2011)."

Robertson, Lycouris, and Johnson describe "complex systems" as "generally diverse and made up of multiple interconnected elements. They are adaptive in that they have the capacity to change and learn from events (Robertson et al., 2007)." The authors further indicate that dance performances with interactive media are an example of such a complex system "in action." The transference of such a performance into a public space may alter how individuals move or behave within it. Gannon's *Mimus* and Cuan's *OUTPUT* as installation are two examples of such "complex systems" and the "interactive media" are robots, animations, and videos. Participants' motions are captured and become part of the installation in both *OUTPUT* and Gannon's *Mimus*. Heightened human motions or behaviors result in a more kinetic and possibly compelling installation in both. In contrast to *Mimus*, the *OUTPUT* installation allows participants to see their own motion as captured by the system and modulate it accordingly. In doing so, *OUTPUT* 1) lends an explicit contrast between that of the moving robot and their own motion, and 2) demonstrates how the human fits into and controls elements of the complex system.

Allowing public participants to extend into and "feel like a robot" is part of the secondary contribution of the *OUTPUT* work and probes the motivating question of automated motion. One benefit of this exercise is recognizing the manners in which we ourselves limit, narrow, or mechanize our motions to the requirements of our technologies or the physical tasks in front of us, just as the ABB robot on an assembly line tasked with indenting a sheet of metal or pouring a quantity of silicone. In addition, when the collaborative team - including roboticists and dancers alike - attempted to debug their own work, they were often confronted with the obstacle of the robot's sensorimotor capabilities being quite different than their own. Gesturing or moving like the robot communicates its limitations to collaborators and also provides clarity on the intended robot trajectory. These limitations are a chasm in public understanding as well: roboticists are starkly aware of the shortcomings in today's robots, while the public frequently sees edited videos, finalized products, or unilateral success stories. This may lead to inflated expectations of what robots can do, while an embodied personal experience of "feeling like a robot," through a work like *OUTPUT*, may open the door to an original perspective.

As with many types of artworks, the questions posed by the *OUTPUT* work may not have a singular answer. Audiences and participants described wonderment at their own body's expressive capacity contrasted by the robot's limited degrees of freedom. Several individuals noted that dancing with representations of themselves and the robot made them feel multifaceted. Others inquired where the real robot was, as if the true presence of the robot could alter or reaffirm their beliefs about it as viable choreographic source material.

When the augmented reality app launches to the public, participants will film dances of themselves alongside the Wen robot and share them with the artist. This will give them an opportunity to try the human-robot interaction task that the aforementioned artists and Cuan investigated in their works: how the robot body will affect their own.

CONCLUSION AND FUTURE WORK

OUTPUT was generated primarily during a 12 weeks residency in summer, 2018, and revisited in summer, 2020. Components of the work have been presented in three formats: as a performance, an installation, and a smartphone application. Two pieces of software, a choreographic process, an improvisational structure, films, and dances were created. The primary artistic motivations were exploration of pure movement across recording mechanisms (and the agency or lack thereof that emerges), as well as the robot's repetition and utilitarian applications sparking choreographic ideas, variations on a recurrent theme, and participant reflection about interface-enforced repetition in their own lives.

Future instantiations of this work could include surveys or recorded interviews to gauge how audience members interpreted and experienced the fundamental questions around embodiment and robot perception. In order to further explore the public involvement in the work, a permanent or long term home for the *OUTPUT* tools (rather than short term installations that require portability) would permit the artistic team to setup the Wen or a physically similar robot alongside. This fully embodied robot installation would underscore the themes and provide new opportunities for aesthetic and interactive investigation. The *OUTPUT* piece explores some similar themes as other installation and performance works involving industrial robots. *OUTPUT* extends the historical context of industrial robots in performance further by not only bringing an inaccessible robot into close proximity with the public, but also equipping participants with improvisational and directorial tools in nascent mediums (AR) to reevaluate their impressions of themselves and industrial robots.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

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Exploring Co-creative Drawing Workflows

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This article presents the outcomes from a mixed-methods study of drawing practitioners (e.g., professional illustrators, fine artists, and art students) that was conducted in Autumn 2018 as a preliminary investigation for the development of a physical human-AI co-creative drawing system. The aim of the study was to discover possible roles that technology could play in observing, modeling, and possibly assisting an artist with their drawing. The study had three components: a paper survey of artists' drawing practises, technology usage and attitudes, video recorded drawing exercises and a follow-up semi-structured interview which included a co-design discussion on how AI might contribute to their drawing workflow. Key themes identified from the interviews were (1) drawing with physical mediums is a traditional and primary way of creation; (2) artists' views on AI varied, where co-creative AI is preferable to didactic AI; and (3) artists have a critical and skeptical view on the automation of creative work with AI. Participants' input provided the basis for the design and technical specifications of a co-creative drawing prototype, for which details are presented in this article. In addition, lessons learned from conducting the user study are presented with a reflection on future studies with drawing practitioners.

Keywords: human-robot interaction, drawing, user study, co-creative AI, collaborative AI, creative computing

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1. INTRODUCTION

Some art forms feature well-understood and well-explored traditions of collaboration, such as *improvisation* in music. Within drawing practise, collaborative or co-creative drawing is rare and less explored. The use of state-of-the-art technology to facilitate collaboration or inspire creativity has been considered in both music (e.g., Carot et al., 2020) and visual arts (e.g., Lewis, 2008; Kowaliw et al., 2012). At the same time, recent developments within and broader awareness of *Artificial Intelligence (AI)* have expanded the notion of human-computer co-generated creative content. In our work, we are interested in exploring how AI technology might contribute toward an artist's drawing workflow. Here, we present the results of a preliminary user study which we conducted in Autumn 2018 with two key objectives: (1) to gain understanding of drawing practitioners' current working environments and uses of technology, both in their everyday lives and in their art practice; and (2) to speculate with drawing practitioners on ways in which intelligent devices might collaborate with them, providing opportunities to enhance rather than detract from their art practice. Our analysis concentrates on identifying features and challenges to address in the next steps of our research programme: the development of a prototype system designed to enable AI-supported collaboration in co-creative drawing practice.

The aim of our preliminary user study was to be *exploratory*. Instead of relying on our own assumptions about how contemporary drawing practitioners work, we interrogated participants explicitly through survey questions and implicitly through observation of their drawing, captured on video, and provided them with an opportunity for reflection through a semi-structured interview. During the interview, we proposed to drawing practitioners the notion of a co-design space in which they could draw alongside an AI collaborator. These discussions led to a number of interesting observations and discovery of misconceptions, both on the part of the practitioners with respect to AI and on our part with respect to practitioners' willingness to consider human-computer co-generation of creative content.

Why do we believe that this study is of interest to the Robotic Arts community? In this community, people are concerned not only with robotic systems as art pieces—*artifacts*—but also with robotic systems that are part of the *process* of creating art. This user study is most applicable to the latter group, particularly with respect to human-robot interaction research (as elaborated in section 2 on Related Work). In our envisioned prototype system, our non-traditional "robot" is embodied within an intelligent system that assists a drawing artist in a variety of ways, as explored in this article. In this case, our system is learning through observation, i.e., learning by watching an artist draw. Eventually, through such learning and computational creativity models, robotic art systems might be able to embody more surprising and novel artistic styles. But, perhaps, the most novel outcome will be the collaborative relationship between a robot and their fellow artist.

This article is organized as follows: section 3 details the design of our user study, after which, the results are presented, split into two sections. Section 4 presents subjective analysis of results: how the participants described their drawing practice based on responses to our paper survey and discussions in the semi-structured interview. Section 5 presents objective analysis of results: we reviewed the video of participants drawing, captured during the sessions, and computed statistical metrics as well as considered image processing techniques to characterize aspects of their drawing process. Section 6 describes the next steps in our research programme: how we are currently applying the results from the study to the design and development of our prototype human-AI co-creative system. In section 2, we place our investigation into a wider context by highlighting pertinent related work. Key factors, identified during the user study, that influence the design of our prototype system are discussed in section 7. Finally, a summary of our study, reflection on lessons learned and plans for future work are shared in section 8.

2. RELATED WORK

In this section, we look at works related to the topic of collaborative drawing between human artists and machines. First, we consider the studies of human artists and designers, either drawing solo (section 2.1), as well as recent research into drawing collaboratively (section 2.2). Then, section 2.3 contains a brief review of systems that generate drawings independently, either through bespoke programming, through rule-based systems or through learnt models. Both robotic drawing systems that draw physically and software-based digital drawing systems are considered. In section 2.4 we then review the state-of-the-art in co-creative drawing systems, where the drawing interaction is between humans and machines. Finally, section 2.5 identifies the gaps in the prior work that motivates the exploratory study.

2.1. Artists Drawing Alone

First we look at research on artists drawing by themselves and the technology used to study their practice. Video recording serves as the primary basis of early studies of drawing. Empirical psychological studies in the 1970's and 1980's involved hand annotation of videos showing the movement of an individual's hand and pencil to produce drawing (Van Sommers, 1984). The research output was a systematic catalog of features, such as the stroke order and preferential directions in mark-making between right-handed and left-handed individuals. The aim of these studies was to go from the mechanistic understanding of how drawings are produced to arrive at conclusions in how cognition plays a role in both representational and abstract drawing. The authors concluded that drawing was a vertical process, built up in layers, from drawn strokes, geometric primitives to conveying meaning through *graphic acts*. In addition, they conclude that artists are not conscious of the "structure and complexity of their own conduct" and requires a broad variety of analytical methods to understand drawing (Van Sommers, 1984, 270).

Saliency analysis, or analysing the movement of an individual's eye fixation to understand where the their attention lies, is another form of analysis used to understand drawing. One set of studies developed a gaze shift theory that describes the movement of an artist's attention between the canvas and the subject in observational drawing, with noted differences based on the artist's experience (Miall and Tchalenko, 2001; Tchalenko and Chris Miall, 2008; Tchalenko et al., 2014). Saliency analysis has also been used to try to understand eye fixation when drawing different categories of objects (Sarvadevabhatla et al., 2017).

Where eye tracking often requires wearing specialized sensors, other drawing studies approach observing an artist as unobtrusively as possible. A recent study of the painting process used a mixed-sensor approach comprising multiple cameras and microphones attached to the canvas (Fernando et al., 2018; Weiler, 2020). This research transforms the sensor data from the artist's drawing session into novel visualizations, such as time-lapsed video and 3D printed relief representation in order to provide the artist a means to reflect on the latent processes involved in completing the artwork.

2.2. Collaborative Drawing

Design sketching, or using sketching in the design process for architecture and engineering, has been studied as a communication tool between multiple human designers. In particular, comparing in-person human-to-human sketching to that of collaborative human-to-human remote sketching in terms of multimodal communication (Eris et al., 2014) has been studied. Studies also analysed the use of sketching and gesturing and compared how they differ when done in-person on a shared canvas to that on digital shared canvas (Zurita et al., 2008) or virtual environment (Gül and Maher, 2009). In design sketching, the sketch is not the final output. Instead it is a part of the process to achieve a design goal. In this regard, the sketching is different to that of illustration, where the drawing is the intended produced artifact.

Within the *drawing research* community (Garner, 2012), there has is an increasing interest in documenting the wide number of collective and collaborative drawing practises among artists (Journeaux and Gørrill, 2017). Often these practises involve drawing together either in person or via postal correspondence between two [e.g., the *Inappropriate Shift* project (Baker and Foster, 2017)] or a larger distributed group [e.g., the *Brew International Drawing Circles* (Brew and Journeaux, 2017)]. These collaborative practises are not technologically mediated, beyond coordination via e-mail or messaging application, and thus the drawing is analog in medium.

However, a very recent work (Parikh and Zitnick, 2020) in understanding human-human collaborative sketching takes the form of a crowd-sourced study. Using an online digital application, multiple individuals take turns sketching a scene with a finite stroke limit. In addition to taking turns, the individuals can vote on versions of the sketch to decide on which sketch will be used in the next round of collaboration. They found that this collaborative-voting strategy produced the highest perceived creativity in the results of their experiments. Also, unlike very personal relationship-based collaborative practices mentioned previously in the drawing research community, this collaboration is performed anonymously with individuals only communicating through what they draw and how they vote.

2.3. Robotic Systems Drawing Alone

Traditionally, human-robotic collaboration in the visual arts consisted of artists programming robots to draw imperatively. Perhaps the most classic robotic drawing systems is the *AARON* robot (McCorduck, 1991), which was programmed by the artist Harold Cohen to paint in a manner that he concluded was an extension of his own artistic style (Boden and Edmonds, 2019). Similarly, the portraiture robot, *PAUL* (Tresset and Fol Leymarie, 2013) drew real-life subjects via computer vision system. Like *AARON*, the style of the drawing was strongly influenced by its creator (Patrick Tresset). A contrasting approach toward drawing is relying on *emergence* and the complex interactions of a swarm of robots to produce a drawing, such as the *ArtSBot* and *Robot Action Painter (RAP)* systems (Moura, 2016).

An iconic project which embodies the spirit of constructing drawing systems is *The Painting Fool* system (Colton, 2012). While not a robotic system, it is a fully automated painter, which is software that simulates the behaviors of human painters. It makes choices about art materials and painting style and simulates strokes on canvases. In addition to producing work, it is a *Creative Computing (CC)* system which describes the output, through generating text and arguments about the produced work.

All of these systems incorporate a specific set of rules that drive the creation of the art. Some are large hand-developed systems of rules that were constructed over time, such as *AARON*. Others were a few simple rules, which relied on the complex interaction of many autonomous drawing robots to produce complex artworks, such as the *ArtSBot*.

In recent years, *Machine Learning (ML)* advancements in deep learning and neural networks and in particular the outputs from *Generative Adversarial Networks (GANs)* (Goodfellow et al., 2014) have produced a series of "AI Art" systems (McCormack et al., 2019), some of which were controversial by making large sales on the international art market (Unknown, 2018). These systems differ from the robot drawing systems mentioned previously in that they are entirely data-driven in how they produce the art work. An important distinction to make is that many of these systems are static raster-image based, often utilizing levels of *Convolutional Neural Networks (CNNs)* which produce pixel-level image data. *Style transfer* models are common systems here, which perform image-to-image translation. For example, the *pix2pix* system (Isola et al., 2017) is a style-transfer system capable of rendering a photograph into a painting of a specific artist's style. In terms of drawing systems, *SmartPaint* (Sun et al., 2019) is a painting style-transfer system that creates cartoon landscape paintings via a GAN trained on cartoon landscape images and their corresponding semantic label maps (i.e., images where color values correspond to semantic features). An artist sketches semantic maps, such as where trees and mountains are in a landscape, and the system generates a cartoon painting with appropriate colors and textures. While the authors describe human-machine co-creation in their paper, they also conclude that their machine would benefit from more human ownership in the design process as once they submit the semantic map the painting is generated entirely by the AI. An artist might feel more a part of the creative process if they were able to participate in the painting and creative transformation. to painting, would make the human feel more a part of the creative process.

The output of these models are the pixels of a completed image, where the robot drawing systems mentioned previously produce sequences of drawing actions. In this case, an early deep learning system (Graves, 2014) used *Recurrent Neural Networks (RNN)* to encode the drawing action sequences of doodles. This work was improved upon by the *sketch-rnn* system (Ha and Eck, 2017) which became a very influential neural network representation for sequences of drawing actions. This system uses a sequence-to-sequence *Variational Autoencoder* to encode sequences of drawn strokes learned from a large corpus of crowd-sourced sketches (Jongejan et al., 2016) and has inspired subsequent work in generalizing and modeling sketching (Chen et al., 2017; Cao et al., 2019; Lu et al., 2019).

2.4. Co-creative Drawing Systems

The *sketch-based* interaction research literature is rich with description of tools that provide real-time support to artists while drawing. These tools operate at a range of scales, from the drawing-primitive level, such as beautifying an artist's drawing with idealized geometric models (Arvo and Novins, 2000), to producing entirely new drawings, such as attempting to automatically draw the next frame in a drawn animation sequence (Xing et al., 2015). Alternatively, drawing systems can also support an artist by providing them with supportive imagery as an overlay or underlay to draw alongside. An example of this is the *ShadowDraw* system (Lee et al., 2011), which provides the artist with processed gradients from an object category database to draw over.

While there is interaction with the computer and the artist in these systems, there is not the encompassing goal to provide a truly co-creative experience between the artist and their drawing process. Co-creative systems expect the AI to be collaborating with the artist in the production of the artwork. An example of such a system is the *Drawing Apprentice* (Davis et al., 2016a,b), an improvising drawing agent that analyzes the user's input and responds with its own artistic contributions within a shared digital canvas. The AI can draw either by taking turns or asynchronously, and the artist has the ability to correct the AI as it is in the process of drawing. In addition, the Drawing Apprentice utilizes real-time object recognition on the artist's drawing as part of the inputs of the system. The artist is able to select drawing modes where the AI can trace, transform mimic the their drawn input.

The *sketch-rnn* model spurred the development of co-creative sketching systems. *collabdraw* (Fan et al., 2019) is a web-based collaborative sketching environment that uses the *sketch-rnn* model to allow an artificial agent to collaboratively sketch with a human with a well-defined visual concept from its sketch database (i.e., "Let's draw a bear together"). While the sketching goal was constrained, the authors were able to show in user studies that the collaborative sketches contained as much semantic content as those produced by the humans on their own. In *collabdraw*, the human and AI alternate strokes in a turn-by-turn manner. In contrast, an example of a continuous drawing system is *DuetDraw* (Oh et al., 2018). This system integrates *sketch-rnn*'s capabilities into a variety of tools that the AI can utilize with varying initiative in collaborative drawing. It can complete the artist's sketch, transform the sketch into a different style and recommends empty space on the drawing canvas for the artist to fill. In addition, it utilizes the *PaintsChainer* (Yonetsuji, 2017) style-transfer model in order to colorize a sketch. The drawing agent also communicates with the artist during the drawing process to explain why it is taking certain actions. *DuetDraw* is also an example of a system that fuses existing AI drawing models within the same interface.

The interaction between the artist and the AI does not need to involve the AI drawing directly on the art piece. The *Creative Sketching Partner (CSP)* (Karimi et al., 2019) is a co-creative design system that collaborates with a designer on a shared design task. In order to prevent design fixation, the CSP uses *conceptual shifts*—a conceptual model that guides users toward different aspects of a design space based on visual and conceptual/semantic similarity. Utilizing the *QuickDraw* dataset (Jongejan et al., 2016) as a database of sketch designs that can be related to the working sketch both visually and semantically, it present the designer with a novel sketch that is visually similar but semantically different.

Co-creative collaboration can also occur beyond the digital canvas but in physical space. The *DialogCanvasMachine* (Cabannes et al., 2019) was a physical interactive installation involving an artist duo, Tina&Charly, who already have a collaborative painting practise, and an AI using the *sketch-rnn* model trained on the *QuickDraw* dataset and a catalog of the artists' work. The three collaborators take turns painting on a canvas in their own unique color. During the AI's turn, it takes a picture of the canvas and responds by projecting suggested strokes onto the canvas, which are interpreted by the artists and painted onto the canvas. Like the *Drawing Apprentice*, the artists have the ability to interpret and edit the contribution of the AI to the painting.

Human-robotic collaborative drawing is another example of art-making in physical space. The *D.O.U.G* system (Chung, 2015) involves an industrial robot collaborating with the artist Sougwen Chung to produce paintings. The robot is programmed to mimic what the artist is drawing and in turn the artist can respond to what the robot is drawing (Sandry, 2017). This occurs upon the same canvas in a real-time continuous manner. Another collaborative robot painting project is the *ArtTherapyRobot* (Cooney and Menezes, 2018; Cooney and Berck, 2019). This system's goal is to conduct research into socially assistive robotics for art therapy. Using a Baxter[1] robot, the system and the artist paint separate pieces or take turns painting on the same canvas. The robot operates in two painting modes, one where it imitates the artist's painting. In the mode it attempts to sense the emotional state of the artist and contributes to the painting according the a visual metaphor model.

2.5. Conclusions

Our search of the literature with respect to co-creative or collaborative drawing amongst humans and machines was broad. The related work shows that there is a history of studying artist's drawing through technology (section 2.1), a body of research into humans drawing collaboratively (section 2.2), a rich history of computational creative systems drawing autonomously (section 2.3), as well as recent research into co-creative drawing systems (section 2.4). Three motivations for our user study arose from the related work.

Previous research appears to assume that co-creative drawing is a mode well-understood by practicing artists. While there are studies into artist's drawing behavior (section 2.1) and human-human collaborative drawing (section 2.2), we are unaware of any study that discusses directly with practicing artists their attitudes toward and the opportunities for co-creative drawing systems. Thus, our preliminary survey was motivated by a desire to explore these specific questions with practicing artists and pose direct questions to them about working with an AI-driven assistant.

In section 2.4, we see that some co-creative systems are evaluated through user studies, such as testing *conceptual shift* techniques with the *CSP* (Karimi et al., 2019). However, we are not aware of any preliminary study involving practising artists contributing toward the design of a co-creative drawing system. Systems, such as the *DialogCanvasMachine* (Cabannes et al., 2019) or *D.O.U.G.* (Chung, 2015) were developed in conjunction with a single artist or artist duo. Or, system designers were themselves artists who developed a suite of co-creative drawing systems, such as the *Drawing Apprentice* (Davis et al., 2016a). We

[1] https://robots.ieee.org/robots/baxter/.

see our preliminary study as an opportunity to inquiry multiple and possibly contradicting perspectives onto the possibilities of co-creation between a human and an artist.

Finally, robotics and sensor fusion provide opportunities for co-creative systems to operate with artists working with physical mediums. The *ArtTherapyRobot* (Cooney and Menezes, 2018), *D.O.U.G.* (Chung, 2015) and the *DialogCanvasMachine* (Cabannes et al., 2019) are inspiring examples of co-creation in physical space. Given the dominance of digital drawing tools within an artist's practise, we wanted to use the preliminary study to discuss the use of physical mediums and the opportunities for co-creative drawing with them.

3. DESIGN OF PRELIMINARY USER STUDY

This section describes the design of our preliminary user study which we conducted in Autumn 2018. The objectives of the study was to improve our understanding of drawing practitioners' working environments and their views toward a future system in which they could draw with an intelligent "robotic" collaborator. Recruitment for the study was done via email solicitation to a university research study recruitment channel, art schools and London based drawing communities. Respondents were filtered to balance 3 classes of participants: part-time drawing enthusiasts, full-time professional illustrators and full-time illustration students. In total, 21 participants were interviewed individually for 90–180 min sessions each consisting of three activities: a paper survey (section 3.3), a series of video-recorded drawing exercises (section 3.4) and a semi-structured post-interview (section 3.5).

3.1. Ethical Clearance

This study was carried out in accordance with the recommendations of the Research Ethics Office of King's College London as Low Risk Research, approved by the university's Biomedical & Health Sciences, Dentistry, Medicine and Natural & Mathematical Sciences Research Ethics Subcommittee. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

3.2. Demographics

The study had 21 participants, representing a balanced mix of three groups: professional illustrators ($n = 7$), part-time drawing enthusiasts ($n = 8$) and illustration students ($n = 6$). Gender-wise, the group skewed two-thirds female. However, a majority of full-time artists are male. Age-wise, the majority of students and part-time drawing practitioners represented the younger (<25) group, whereas the full-time artists were spread across the older groups (25–40 and > 40). **Figure 1** illustrates the demographics.

3.3. Paper Survey

As the first activity, each participant completed a 21-question paper survey consisting of multiple choice and free response questions about their drawing habits, technology usages and attitudes. The survey was divided into three sections: Background, Drawing Practise, and Technology (usage and attitudes). **Table 1** contains the text of each question, identified as **Q1** through **Q21**. A copy of the survey is available in the **Supplementary Material**. The survey elicited four different types of responses: (a) multiple choice only; (b) multiple choice with open-ended "other" option; (c) open-ended only; and (d) positive scale (i.e., 0..*N*).

In section 4.1, we analyse the 15 questions that contributed most to our objectives: gaining understanding of drawing artists' current working environments and technology usage and speculating on ways in which intelligent devices might collaborate with drawing artists to enhance their practice. Other questions (**Q5, Q6, Q8, Q16, Q19, Q21**) queried broader baseline aspects of the participants' drawing practise and attitudes toward technology. In the end, we did not find them pertinent as contributing to the design of a co-creative system and did not include analysis of these questions in this paper.

3.4. Drawing Exercises

The second activity was a series of three video-recorded exercises, each lasting ~10 min. Time limits were necessary to implement due to practical factors around scheduling of study participants. In practice, professional drawing may be constrained by deadlines (e.g., publication or exhibit schedule) or more open-ended (e.g., fine art). Artists may behave differently depending on what motivates their drawing, so we designed the study to prompt three different "types" of drawing. Participants drew from *observation*, from *recollection* and from *imagination*, as explained below. The order of the exercises was the same for each participant. The post-interview (described in section 3.5) captured artists' impressions of these different exercises and how they relate to their own practice (see section 4.2.1. The prompts given to the participants were as follows:

A. **Observation**: *Here is an arrangement of objects on the table for you to draw, however you feel fit.*
B. **Recollection**: *Next, from memory without any reference material, draw a bicycle, or bicycles.*
C. **Imagination**: *Finally, do some free drawing, which could be anything, real or imaginary. It could be many things, or one specific thing. Draw anything.*

For exercise A (Observation), they were presented with a small set of objects (e.g., coffee cup, small figurines, and plastic fruit). The layout and selection of props varied depending on where the research study setting. Most of the study sessions ($n = 16$) occurred in a studio-like setting in the Interaction Lab at King's College London, while the others took place in participants' studios ($n = 5$). An assortment of drawing tools were available to the participants (see **Table 2**): pencils (various weights and colors), charcoal, pens (various line weights) and graphics markers. In addition, participants were encouraged to bring and use their own personal drawing tools. Results are analysed in section 5.

3.5. Post-interview

The final activity was a semi-structured interview in which we asked a few open-ended questions about participants' drawing practice and discussed follow-up questions about the drawing exercises. In addition, we asked them about their attitudes toward

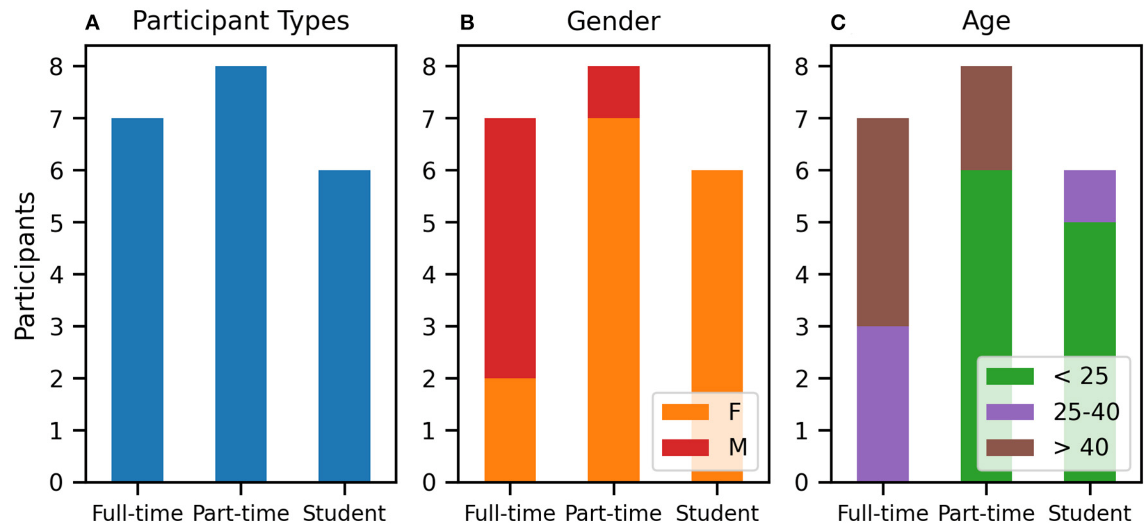

FIGURE 1 | Study participants, showing **(A)** drawing practitioner types, **(B)** gender, and **(C)** age distributions.

TABLE 1 | Survey questions, with reference to the section in which the responses are discussed.

	Question (clarifications given in italics)	Related section (§)
Q1	How long have you been drawing as part of your creative or professional practise?	Experience (§ 4.1.1)
Q2	Have you done any formal training for drawing?	Experience (§ 4.1.1)
Q3	Do you participate in any drawing communities, collectives, groups, or drawing sessions (i.e., life drawing sessions)?	Drawing Prac. (§ 4.1.2)
Q4	Do you earn money from your drawing practise or do you utilize drawing as part of your profession?	Drawing Prac. (§ 4.1.2)
Q5	Rate the extent to which you would describe your drawing as being...	*n/a*
a	...illustrative?	
b	...abstract?	
c	...drawn from real-life? (rendering an object, setting or subject that you directly perceive)	
d	...drawn from personal memory? (rendering an object, setting or subject that you perceived in the past)	
e	...drawn imagination?	
f	...an expression of emotion?	
Q6	How frequently do you doodle or make drawings while your attention is otherwise occupied (i.e., draw absentmindedly during a meeting in the margins of a piece of paper)?	*n/a*
Q7	Which drawing mediums do you most typically draw with?	Media&Tech. (§ 4.1.3)
Q8	When do you draw? Is there a regular time (i.e., in the morning, late at night) or routine (i.e., with a coffee, after a long walk) that you have with your drawing practise?	*n/a*
Q9	How long are your drawing sessions typically?	Timing (§ 4.1.4)
Q10	How do you typically work? (*How often do you take a break while working?*)	Timing (§ 4.1.4)
Q11	How do you typically focus your work during your drawing sessions?	Timing (§ 4.1.4)
Q12	What is your drawing environment like?	Environment (§ 4.1.5)
Q13	Are there things about your drawing environment that you would want to change to make it a more ideal work setting?	Environment (§ 4.1.5)
Q14	Do you carry around a sketchbook or a portable drawing pad?	Media&Tech. (§ 4.1.3)
Q15	Do you practise collaborative or collective drawing with another person or persons?	Drawing Prac. (§ 4.1.2)
Q16	Which of the following technologies do you utilize on a regular basis?	*n/a*
Q17	Which of the following technologies do you utilize as part of your drawing practise?	Media&Tech. (§ 4.1.3)
Q18	Which of the following technologies do you utilize to capture, document, or archive your drawn work?	Media&Tech. (§ 4.1.3)
Q19	Which of the following ways do you use to share, distribute, or sell your drawings?	*n/a*
Q20	How interested would you be to utilize more technology in your drawing practise?	Interest (§ 4.1.6)
Q21	Is there anything else that you would like to say or comment on?	*n/a*

Questions with related section marked n/a are not explicitly analyzed in this article as the results were not deemed useful with respect to the explicit objectives laid out in section 1. Question numbers are color coded: (red) multiple choice only; (orange) multiple choice with open-ended "other" option; (yellow) open-ended only; and (blue) positive scale (i.e., 0...N). The full survey for the study is available in the ***Supplementary Material****.*

TABLE 2 | Drawing tool usage.

Tool	Number of artists
Charcoal	4 (19%)
Eraser	**12** (57%)
Finger smudge	2 (10%)
Graphite	2 (10%)
Marker	7 (33%)
Pastels	1 (5%)
Pen	**12** (57%)
Pencil	**17** (81%)
Stylus	1 (5%)
Watercolors	1 (5%)

Bold indicates most common tools used by participants.

AI and envisioning potential collaboration with a drawing AI. We utilized three prepared questions to spur discussion, initiated by each of the prompts listed below:

1. **Drawing Practice**: *Reflect on the drawing session, how does this compare to how you use drawing in your work and part of your creation process?*
2. **Attitude toward AI**: *I [the interviewer] am interested in collecting people's viewpoints about what they perceive about Artificial Intelligence (AI). The term AI has changed a lot in the media in popular usage and culture over the years since when I studied it. For example, at one point graphical user interfaces were considered AI because of the novelty of using a visual interface to interact with a computer. What does AI mean to you?*
3. **Co-design Question**: *I [the interviewer] am interested in developing a technical tool that artists can collaborate with in their drawing practise. While there is a definitive digital practise with drawing, I am investigating whether there is still value in having artists working and drawing with traditional media (i.e., pen and ink on paper). I envision this artist tool as observing and responding to what the artist is drawing on the page in a real-time process. Such a tool could be a form of sketchbook that has a sense of what you have drawn before, or an improvising partner in collaborative or collective sketching. Based on your experiences with drawing, and your drawing practise, I'm interested in hearing your reaction and ideas around such a system.*

Results are analysed in section 4.2.

4. SUBJECTIVE RESULTS: SURVEYS AND INTERVIEWS

In this section, we discuss the results and subjective analysis of the first and last components of the study: answers to survey questions and feedback obtained during the semi-structured interview.

4.1. Survey Results

Capturing information about the drawing tools and technology usage of participants is key for understanding the range of physical art media that drawing artists employ and thus highlight potentially important features of our prototype co-creative drawing system. Since the aim of our survey was exploratory, some questions proved to be more relevant than others for the purposes of guiding the design of our prototype. Here we focus on the questions (listed in **Table 1**) which provided more pertinent answers, addressed accordingly in the following sub-sections.

4.1.1. Experience and Education

With regard to experience, all of the full-time artists and half of the part-time artists and student participants reported to have been drawing for longer than 10 years (**Figure 2**, **Q1**). Most participants have had some formal drawing education (**Figure 2**, **Q2**). Both the full-time artists and the student participants had preparatory (A-level or foundation level) drawing instruction or some form of university drawing training. Extra-curricular drawing training, such as workshops or continuing education drawing courses, were the most common form of training for part-time participants. Less common across all of the participant types were personalized modes of drawing training (e.g., one-on-one tutorials or apprenticeships).

4.1.2. Drawing Practices

Participation in drawing communities was most reported by all full-time artists, and over half of the part-time artists and students (**Figure 2**, **Q3**). The most common kinds of drawing communities people participate in are regular life drawing courses and urban sketching meet-ups.

All of the full-time artists and students reported making money with drawing (**Figure 2**, **Q4**). Professional activities described were illustration (full-time and freelance), selling artwork at art fairs and online and doing bespoke commissions, such as portraits or commercial sign painting.

Collaborative or collective drawing activity was nearly non-existent for part-time artists and students (**Figure 2**, **Q15**). But a majority of full-time participants have reported to have had some experience. How the participants interpreted collaborative or collective drawing varied (as there was no definition given on the survey, see **Q15** in **Table 1**). Example interpretations for collaborative drawing included sharing drawings with each other at life drawing classes or drawing on each other's canvases in a round-robin style for limited periods of time.

4.1.3. Mediums, Tools, and Technologies Used to Draw

Our survey asked about the kinds of mediums artists use for drawing, either *analog* (drawing with physical media) or *digital*, as these answers help inform the technical design of our prototype system and assess the novelty of our approach.

Pencil is universally used by all research participants, with pen and ink and water-color being common types of analog media (**Figure 3**, **Q7**). In addition, sketchbooks are used by a majority of the participants (**Q14**). All of the student participants use

TABLE 3 | Q13 Responses to "Are there things about your drawing environment that you would want to change to make it a more ideal work setting?".

Type	Things to change about drawing environment (Q13)
Full-time	In terms of comfort, I'd perhaps like a better sofa.
Full-time	One could always use more storage space, work space etc. A quiet space is ideal, but with people coming and going nearby, so as not to feel isolated. I would also like more space for printmaking (linocut etc).
Full-time	I would like to have a private studio.
Full-time	Yes! Would love to have a dedicated "At home" studio space with large longer desk 2–3 m long under a large long window surrounded by plants and good coffee please.
Full-time	Would like to work at home/studio more often!
Full-time	Currently I work from home. It would be nice to be able to make more of a mess.
Full-time	No.
Part-time	More natural light and more nature (but, being in London ...)
Part-time	I like drawing anywhere quiet with good light, but perhaps it would be nice to have a proper studio space.
Part-time	I prefer natural light—sitting by windows—with enough space around me to layout my supplies. I usually put on music or background YouTube videos while drawing.
Part-time	Yes, ideally it would be a separate room where I only draw or paint
Part-time	No
Part-time	Better lighting, a larger surface I can spread my equipment on.
Part-time	A better chair so that I can improve my posture. I am also looking to get a larger table as well as _____ in great ___, such as felt-tips.
Student	Brighter light in my room when it's night.
Student	In my studio in university, I wish I had a little more space, as I do like to spread. At my student house, I wish I had more natural lighting as its a very dark house with only one window (studio apartment)
Student	I think its ideal enough.
Student	Add things for comfort—i.e., a chair with a back so my back doesn't hurt leaning over or footstools.
Student	I'd like more wall space. But I'd also like more people to be around working as well.

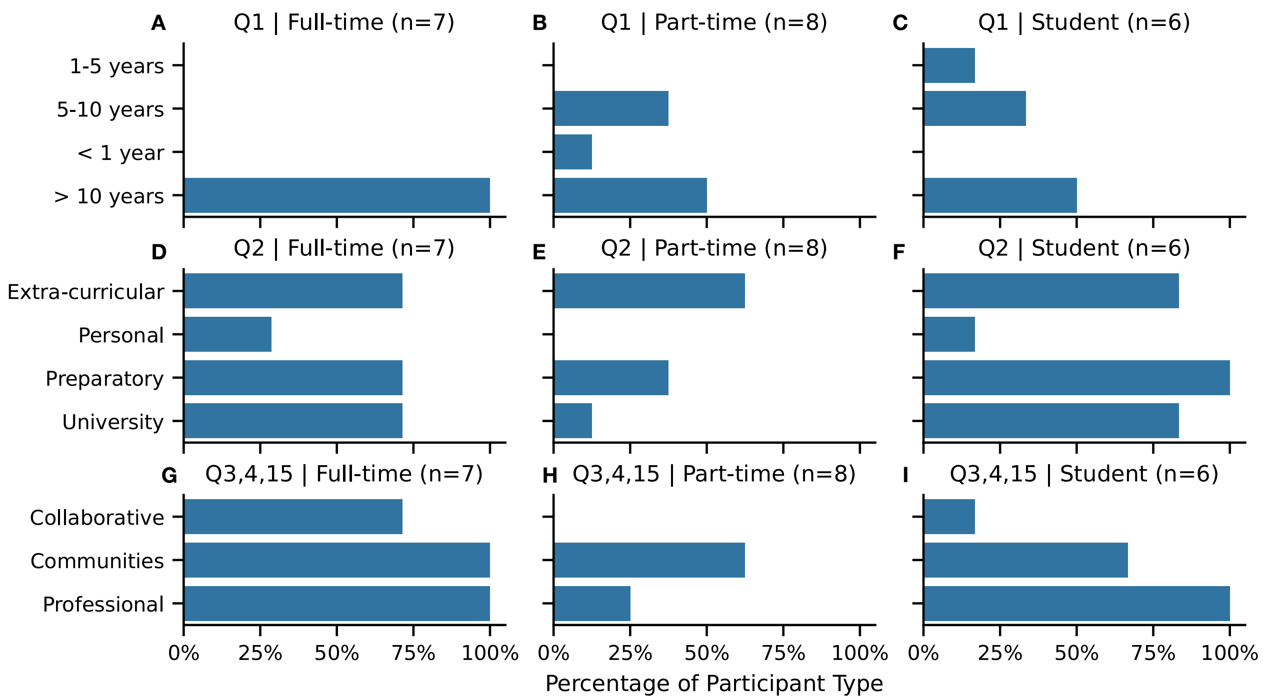

FIGURE 2 | (A–C) Q1. Self-reported years spent drawing. **(D–F)** Q2. Drawing education. **(G–I)** Drawing practise: participation in **collaborative** or collective drawing (Q3), in drawing **communities** (Q4) or as a **professional** drawer (Q15). Abbreviations are in **bold**. Participants selected all answers that apply, except for Q1 where participants selected only one category.

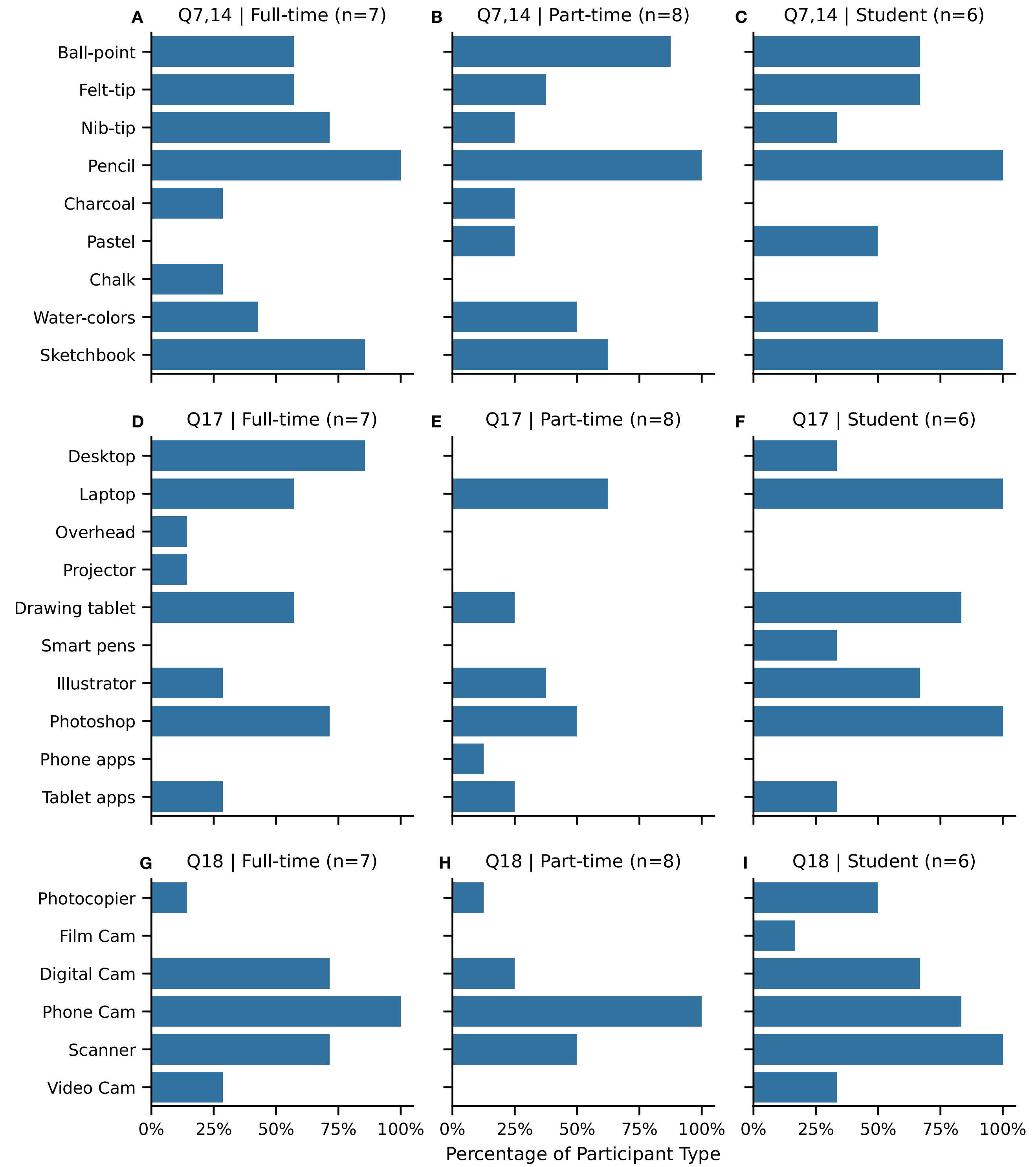

FIGURE 3 | (A–C) Q7. Drawing materials, including pens (**ball-point**, **felt-tip**, **nib-tip**) and Q14. **sketchbook** usage. **(D–F)** Q17. Technology used for drawing, including **desktop** computers, **laptop** computers, analog **overhead** projectors, digital **projectors**, Adobe **Illustrator**, Adobe **Photoshop**, mobile **phone** drawing **app**lications, **tablet** (e.g., iPad) drawing **app**lications. **(G–I)** Q18. Drawing capture technology, including analog **film cam**era, **digital cam**era, mobile **phone cam**era, digital **scanner**, digital **video cam**era. Abbreviations are in **bold**. Participants selected all answers that apply for all questions.

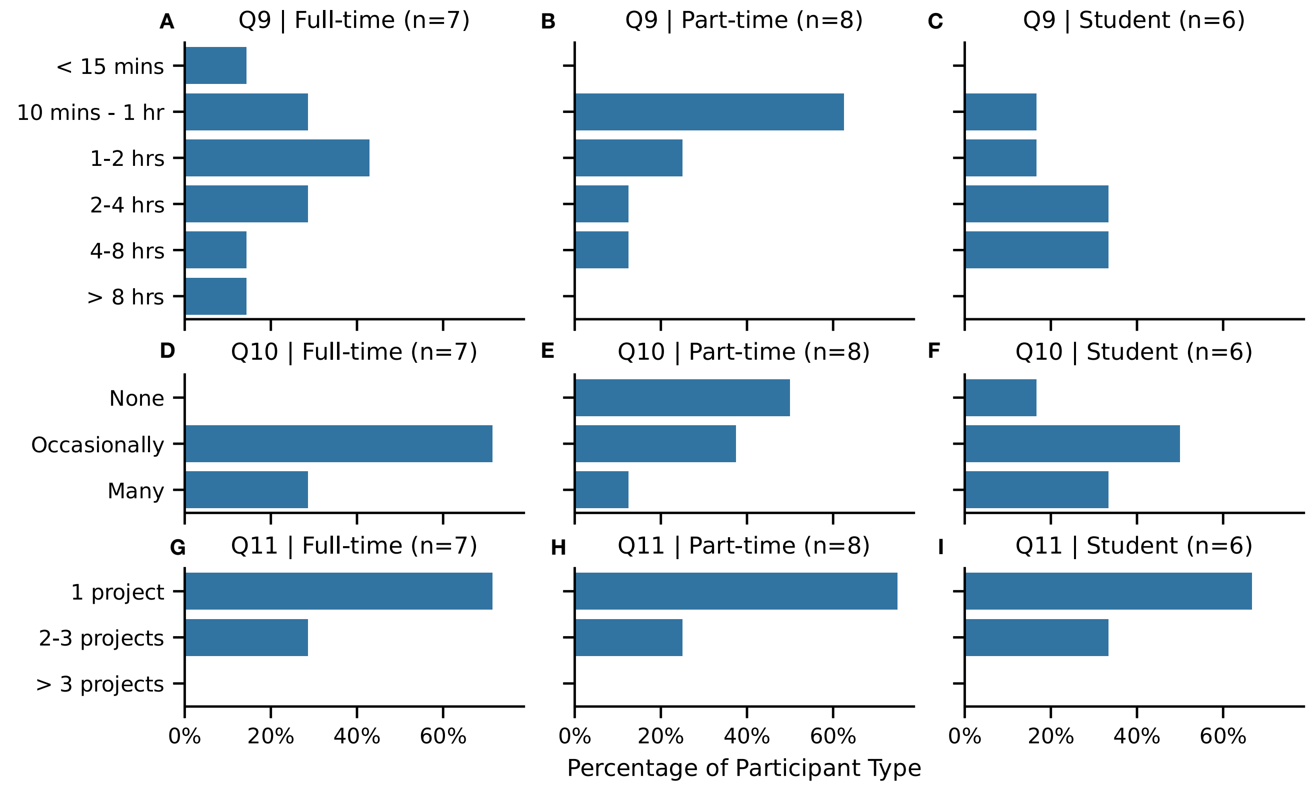

FIGURE 4 | (A–C) Q9. Duration of drawing session. **(D–F)** Q10. Break frequency while drawing: **none** or uninterrupted no breaks, **occasionally** take a break, take **many** breaks. **(G–I)** Q11. Project focus while working: focus on **1** or single project, switch between **2–3 projects**, switch between **more than three projects**. Abbreviations are in **bold**. Participants selected one answer for each question.

sketchbooks, as maintaining a sketchbook is a common activity as part of their drawing curriculum.

With regard to drawing technology (**Figure 3**, **Q17**), a laptop is more common than a desktop, although a desktop is used exclusively by full-time artists and some students. This might indicate a more dedicated work-space or use of university facilities. A specialized drawing tablet is the most common drawing interface. Whereas, tablets, smart pens and mobile phone drawing apps are less common. Software-wise, Adobe Photoshop is more commonly used than Adobe Illustrator. Only one participant uses a projector while working, which means interacting with projected imagery is rare within the study group.

With regard to digital capture technology (**Figure 3**, **Q18**), a mobile phone camera is the most common way to convert an analog drawn image into a digital form. Digital scanners are commonly used as well, in particular amongst student participants.

4.1.4. Timing

How long and how often participants spend time working informs aspects of the technical specification of our prototype system. We want to ensure that the system is practically able to record all of the data generated while an artist is drawing. The participants were asked how long they typically spend drawing in a session (**Figure 4**, **Q9**). Where a majority of part-time participants spend 10 min to 1 h, both full-time artists and students reported longer drawing sessions.

They were also asked to assess how often they take breaks (**Figure 4**, **Q10**), where "occasionally take a break" was the most common response amongst full-time artists and students, while part-time artists leaned more toward "uninterrupted no breaks" response. With regard to switching context between projects during a working session (**Figure 4**, **Q11**), a majority of all participants focus on working on a single project at a time.

4.1.5. Work Environment

Participants were asked about various physical characteristics of their work environment (**Figure 5**, **Q12**), as we are interested in understanding how participants work with respect to different types of distractions within their work setting. Depending on the level of environmental distraction, a collaborative drawing system may have to compete with noise levels, for instance, which could impact design decisions around providing audio feedback to users.

A solitary work environment was the most common response across all participants. In addition, a little over half of the full-time artists and students responded that they also work in shared spaces. Less than 25% part-time artists work in a shared work

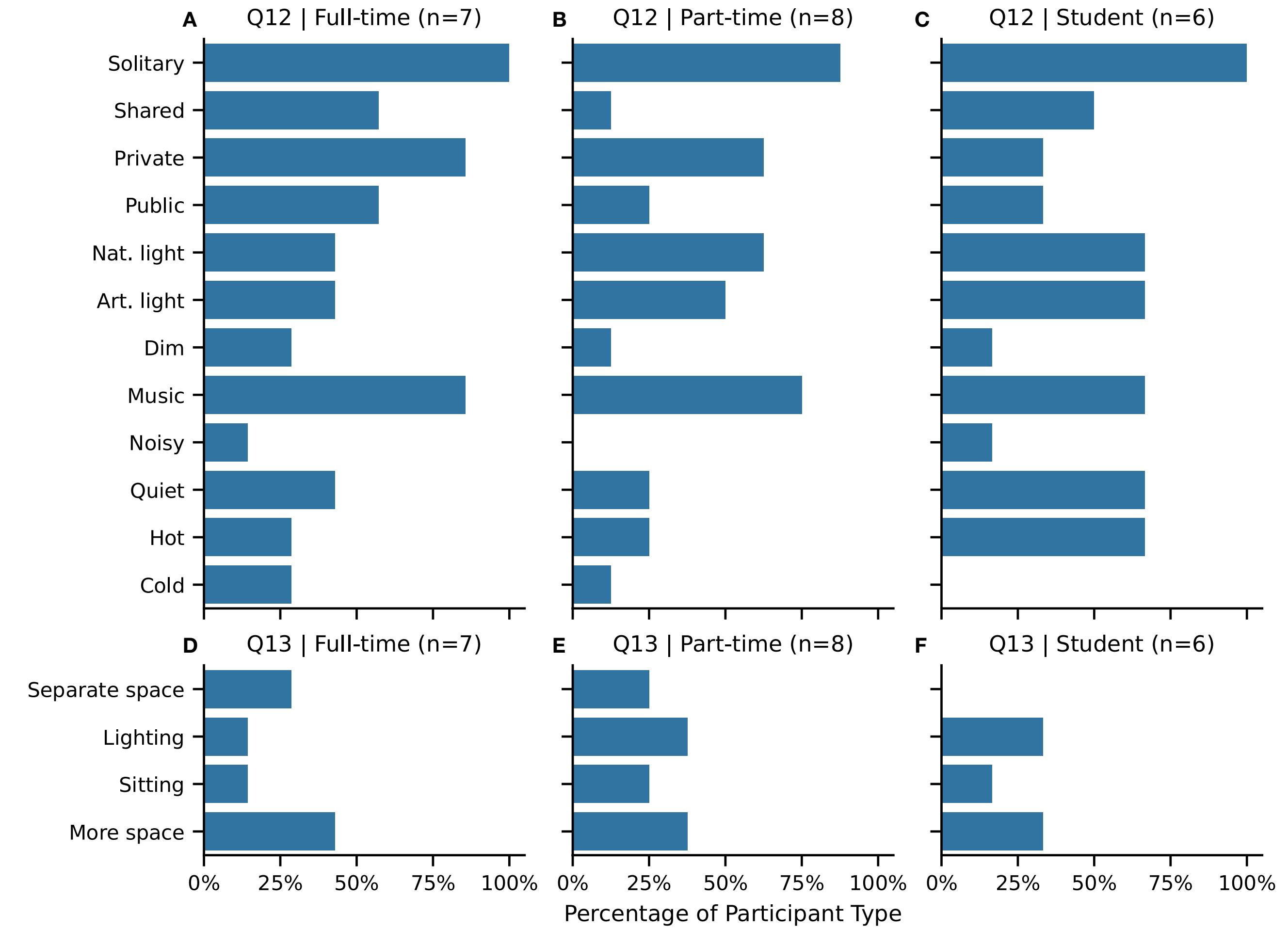

FIGURE 5 | (A–C) Q12. Characteristics of work environment: **solitary** work environment, **shared** work space, **private** setting, **public** setting, **nat**urally bright environment, **art**ificial bright environment, **dim**ly lit environment, listening to **music**, **noisy** environment, *quiet* environment, **hot** (temperature) environment, **cold** (temperature) environment. **(D–F)** Q13. Improvements to the work environment (annotated from the Q13 free responses shown in **Table 3**): dedicated or **separate** studio space, improved **lighting**, improved **sitting**, **more space** or table space. Abbreviations are in **bold**. Participants selected any combination of answers.

space. Private settings are more common than public work settings, overall across all the participant categories.

Half of full-time artists and students and a quarter of part-time artists reported that their work environment was quiet, and almost none of the participants reported working in a noisy environment. Listening to music was one of the most common responses across all participant types.

Bright environments were more commonly reported than dim environments. Overall, there was little distinction between natural and artificial lighting.

Because one's current work environment is often not the *ideal* work environment, participants were also asked about things that they would want to change to make improve their work setting (**Q13** in **Table 1**). A list of their responses are in **Table 3**. We found common themes within the free-responses and encoded them as:

- Having a dedicated, private or separate studio space to work in ($n = 4$).
- Improved lighting or better access to natural light ($n = 6$).
- Improved seating ($n = 4$).
- Having more space to spread out the work ($n = 8$).

Figure 5 shows the annotated counts broken down by participant type.

4.1.6. Interest in Using More Technology

With regard to interest in utilizing more technology in their drawing practice, over two-thirds of each participants group were either "Very" or "Extremely enthusiastic" (**Figure 6**, **Q20**), with the student participants being the highest majority.

4.1.7. Analysis and Discussion

Overall, the surveys contributed a number of findings related to the working habits of our participant group. First, we wanted to verify that certain expected characteristics of different types of drawing practitioners held true. For example: the full-time artists and students draw more than the part-time artists. The full-time artists (and students) make money from their

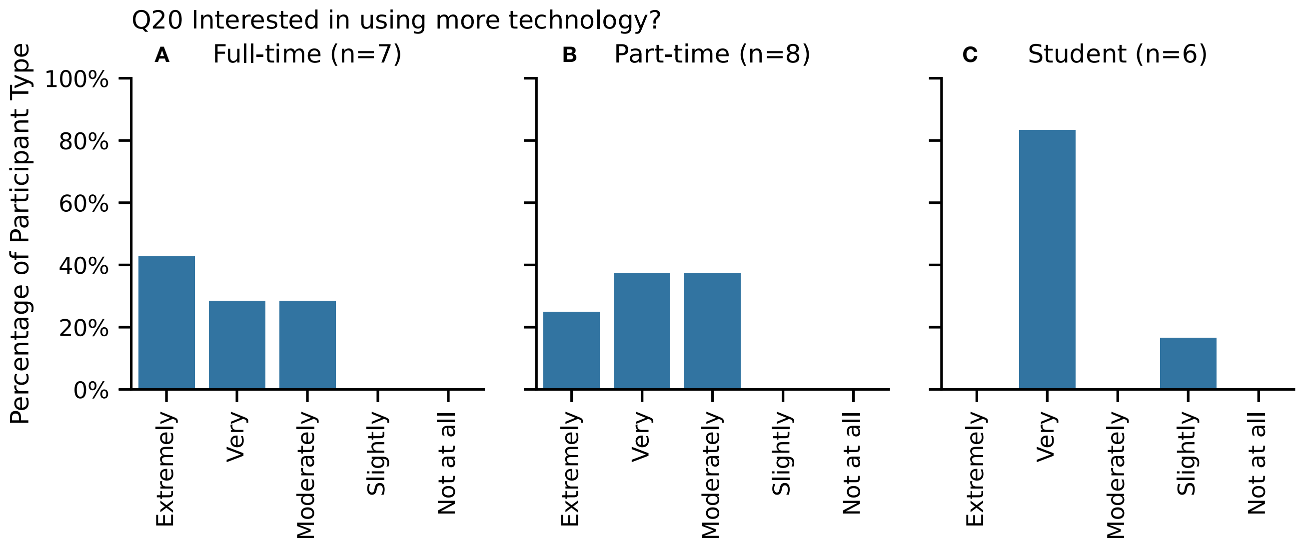

FIGURE 6 | Interest in using more technology for **(A)** Full-time, **(B)** Part-time, and **(C)** Student participants. Participants selected only one answer.

drawing activities, whereas this was less the case for the part-time artists. Second, the survey results provided information about and a distribution for the types of materials that these artists work with, such as pencil being a very common drawing medium. Third, the survey provides an indication for how long a typical drawing session will last, i.e., ranging from 10 min to 1 h, and focus on a single project being the most common activity. Fourth, we are better informed regarding the drawing software and hardware devices participants use, with Photoshop and drawing tablets being very common. Finally, the survey served to prime the interview at the end of the study session. Having the survey answers available during the interview allowed the interviewer to hone in on particular workflows that a participant might follow in creating their artworks.

4.2. Interviews

Each study session began with participants completing the survey on paper, discussed above; followed by executing three drawing exercises (described in section 5) and concluded with a semi-structured one-on-one interview with the first author of this article. Although these sessions were intended to be exploratory, as a guideline we utilized three main prompts (described in section 3.5) to cover the topics of our study. Section 4.2.1 contains analysis of answers to the first prompt, how the participants use drawing in their practise.

The second and third prompts from the interviews focused on participants' attitudes toward AI and then their reaction to the proposal of collaborative drawing with an AI. The participants had a range of attitudes toward AI. However, these attitudes came out more distinctly when considering having an AI drawing partner. Thus, for the purposes of this article, we will focus on the discussions that came out of the reactions to considering what forms AI might take as a co-creative partner, which we discuss in section 4.2.2.

4.2.1. Drawing Practices

The first prompt of the interview explored how participants use drawing. During the interviews, the participants revealed many purposes for their drawing: from commercial illustration, to satisfying the requirements of design school projects, to life drawing in community classes.

While the discussion was initiated by asking them to compare the drawing exercises to how they use drawing in their regular practise, it often led to discussing particular projects and their workflow within those projects. The discussion included what types of drawing activity they do, with what kinds of materials and what kinds of workflows with technology do they utilize in their drawing. This was, by far, the largest and most free-flowing part of the interview process, often going off on long tangents. The aim was to spend time with them discussing their drawing practise without a specific structured flow to the conversation. As part of this process, some participants shared images of their work, or brought sketchbooks or examples of their work to the interview. Some also brought images of their work environment, or demonstrated some drawing techniques that they utilize as part of this portion of the interview. Overall, general patterns of drawing practises vary by participant type.

Part-time artists often do life drawing, or portraiture, usually in a group or life-drawing session. Subjects for their portraits often were their friends or family members. Character drawing, either celebrities or "fan-fiction" style drawing (i.e., their favorite anime characters) was another common practise. It is common for part-time artists to have done a high-school level focus on fine art and illustration. Some part-time artists had an education background in fine art, but decided on other primary career paths. Finally, a few of the part-time artists make money through selling their art works, often in online market places (e.g., Etsy[2]).

Students' drawing practices are primarily consumed by university coursework, although it is very common for them to distinguish between what they are drawing for university compared to what they are drawing for personal or freelance side-projects. The university coursework primarily consists of illustration studio modules for print production or screen. A few of the participants use drawing as part of design studios, such as logo design. *Research drawing* is a common practise, where the students draw from still-life (e.g., the zoo), online images or videos. Another type of drawing that was distinguished is *editing drawing*, or making multiple iterated revisions of a drawing to achieve a final product. One common practise for students is to maintain a project sketchbook, which consists of research drawings, planning and integrating other source media (e.g., cut-outs of images from the internet). The sketchbook is almost always a physical artifact. Students aspire toward careers with drawing. Very common professional aspirations include children's book illustrator, a profession that relies heavily on varied textured illustration (often quite analog or physical). Illustrating graphic novels or comics is another very common aspiration, as is drawing for animation or movies.

Full-time artists described drawing practices more closely to direction given by a client in the form of a brief or a commission. Briefs are common in editorial illustration, providing illustration for a publication, magazine or web-site. In this case, a client might have very vague ideas of what they want and are hiring the participant to contribute creative input. Commissioned work is typically representational drawing: human or pet portraiture from an image or a sitting or architectural drawing of someone's vacation cottage. Other paid work includes drawing in the built environment, either painting murals, sign painting or other text, such as menus for pubs. Another form of paid work is to be a live scribe, that is someone who visually annotates (usually on a white board) a live event, such as a lecture event or a meeting to provide a visual map of images and words as documentation.

Beyond commissions, professionals also generate imagery that they can sell as individual pieces. Often these are prints of illustrations, sold online and at art fairs. Often the original creative work advertises the artist and generates future commissions. Non-paid drawing activity for the full-time artists often consists of participating in drawing communities, in the form of life-drawing classes or urban sketching meet-ups. Personal work is rare, and often it is work with the aim of developing a professional project, such as pitching a storyboard for a movie production. None of the full-time artists are professional studio artists, who typically make a living through the sale of their work through a commercial gallery.

The primary content that all of the participants drew was either observational or illustrative, and most did not mention self-expressive or "free" drawing as being a part of their practice. Painting expressively and channeling their emotional state was mentioned by only one participant. However, *doodling* (i.e., free drawing in the margins of a notebook during lectures or meetings) is an extremely common practise according to question **Q6** in the survey.

Finally, regarding documenting and distributing their work, it was very common for many of the participants to post their work on social media (e.g., Instagram[3]). However, none of them live-streamed or produced videos of their work or process.

4.2.2. Co-designing the Co-creative

This section contains analysis of answers to the third part of the interview, where we discussed the prospect of a co-creative drawing system and how it might have utility in their drawing practise. Here, we are interested in their views on the idea of drawing activity that occurs with an AI observing, processing and/or contributing to artwork in real-time.

As the last question of the interview, a description of the idea of a co-creative drawing system was given. They were asked about their initial reaction and what utility it might contribute to their drawing practise. In addition, they were asked to contribute ideas how it might be useful in their drawing practise. This was to get a response to the proposal of a collaborative drawing AI as well as to brainstorm about what the AI could do or offer to an artist.

In the survey, very few of the participants ($n = 6$, see section 4.1.2) reported to having participated in any collective or co-creative drawing, technology-mediated or otherwise. For most of the participants, they first had to consider what forms of collaborative drawing could take place, in general, regardless of whether it was with an AI or another person.

Based on this, common initial reactions to the question placed the AI in the role of a tutor or fellow peer at a life drawing class—i.e., substituting for human roles that the participants are familiar with. In these situations, the AI would observe the drawing and offer corrections or critiques of the drawing artifact or process. This implies that the AI has some notion, or assumption, as to what the artist is attempting to draw and the "correct" way of drawing or rendering of that image. In the case that the artist is drawing from observation, the AI might also observe the world or still-life being rendered. Alternatively, if the drawing is not from observation, but is representative of a known object or place, then the AI might "guess" or "retrieve" what is to be drawn or is in the process of being drawn and attempt to correct the artist's work in progress. One might think of this *corrective drawing* in the spirit of spell-checking or grammar checking in word processing systems.

Often the discussion led to a point where the idea of a *predictive* element of a drawing AI was mentioned. In this mode, the AI attempts to guess the content that is being drawn, predicts aspects of or a version of the drawing, and presents portions of or the full drawing to the artist. Different scales of prediction are possible, such as the next stroke, or a fully completed drawing. An AI can not only predict and/or make suggestions without prompting from the artist, but also respond directly to the artist, for instance, who might want to know what their drawing "looks like" to the AI and might adjust their drawing accordingly. In addition, some aspects of these predictive uses of AI were

[2]https://www.etsy.com.

[3]https://www.instagram.com.

proposed as a potential *labor-saving mechanism* for the artist. For example, some aspects of drawing is very tedious,especially when it comes to the texturing phase. An artist might be manually filling in a specific texture when exhaustion sets in, leading to deviation from a consistent style. The notion of having an AI complete the task was received favorably.

Scene completion is another, related, form of collaboration that an AI is thought to be able to fill. For instance, some artists work on drawing a character or a portrait, and they would like an idea as to how to fill in a background that makes "sense." In this case this is partially predictive, but also there is an open element here for an AI to be creative in how it might fill in a background or accompanying accessories for the drawing. In this sense, an AI would need to be able to guess the context of the setting that the drawing is within.

An AI might also help to address *artist's block*. This was expressed as a common theme amongst the full-time artists, who draw frequently. In fact, one of the things that they often want to know is if what they are drawing is stereotypical of their own work. In other words, artists might desire novelty in their work, but often rely (subconsciously or otherwise) on habits or "go to" tropes in moments of conceptual difficulty. The problem of deciding what to draw for an artist could be viewed in terms of a form of *exploration-exploitation* trade-off, where the artist is either exploiting their knowledge (i.e., drawing the same thing that has worked in the past) or exploring new directions (i.e., trying to draw something that is novel to them). An AI might be able to contribute to the drawing or show some visuals that help an artist break out of these stale patterns. Often times, participants want to sit down and draw something new, but have a hard time thinking of what to draw. Having an AI that could aid in these moments is appealing to these artists, although the details of how the AI might actually do this was not discussed in depth.

To further expand on the concept of an AI as creative partner, the allegory of Microsoft's *Clippy* [i.e., the digital word processing assistant paperclip from Office '97 (Whitworth and Ahmad, 2006)] was brought up and contrasted with an improvisational accompanist in a jazz combo. Conceptually this was a dead end for our study participants, perhaps because of the lack of clear understanding of how the improvisational analogy translates to the visual arts. For musicians, a clear precedent exists for collaboration in the form of "jamming" together; however in visual arts, this concept is not so clear. This also might be because almost all of the participants' practices were representational drawing, as opposed to free or automatic drawing.

4.2.3. Interview Summary: Key Themes

We applied theoretical thematic analysis (Braun and Clarke, 2006) to the transcripts from the semi-structured interviews. We identified three key themes:

1. **Drawing with physical mediums is a traditional and primary way of creation for visual artists.** Participants expressed clear benefits with respect to drawing with physical art media (e.g., pen, pencil, paint, paper, canvas). Physical surfaces feel immediate and direct (e.g., drawing with a pencil and then being able to smudge drawn lines with a finger). Paper provides a tactile response through friction with the drawing tool. This contrasts to the feeling of working with a digital drawing tablet, which has the haptic response of pushing a piece of plastic upon glass.

> "Pen on glass. I just don't think that it bears. I actually really love—I actually really like doing that today. And I chose this pencil [*referring to a pencil used earlier in a drawing exercise*] because it's chalky it's got sort of—it's got friction. And I like that. Otherwise you can kinda—you can just skid off... Like to actually stop and start. Like I've worked on glass with pens, you've got no stop and no start. You have to be quite definite about where you stop on the page of glass. Whereas, when you're working on surfaces, that surface helps you to sort of slow down and speed up. Does that make sense?"

Even if the final product developed from our current prototype design were to take on a digital form, sketching with pencil and paper often are the initial steps toward embarking on a creative project. Digitizing a physical drawing typically occurs once during a project, via scanning or taking a photo with one's phone, as the effort is high to switch between physical and digital drawing tools. Once digitized, artists reported taking *more time* working on a piece because of the infinite possibilities provided by digital editing.

> "But then actually, I realized... it's actually more time consuming for me to do things digitally. Because I tend to refine things a lot. So if I get a chance to refine it... and there's always something imperfect when I do it digitally. It's like, I could edit it forever. While instead... traditionally sometimes I'll just leave it at that. Or, I'll just edit it slightly here. If I'm drawing something more like colorful or more complicated then I don't bother to scan it. Or I have to go to school to scan it if it's over A4."

2. **Views on AI varied, where co-creative AI is preferable to didactic AI.** When presented with the idea of having an AI collaborator, artists and illustrators expressed a few reservations. They were concerned with something obstructing the direct action of drawing, being stressed by having an observer of their drawing process (even if artificial) and being annoyed at the premise of something instructing them in what to draw. Creative autonomy is important to the artist, and having something intervene within the drawing process is seen as distracting and undesirable.

> (*On a collaborative AI providing drawing suggestions*) "No I don't like it. I don't want suggestions. Like people guessing what you are doing, so I don't like it."

> "I feel like for me, I don't know if I would use something like that because that's also because I have been drawing for so long, so I am used to my process or whatever."

On the other hand, artists were open to idea of having an inspirational agent, or muse, to contribute toward their idea process. Sometimes, coming up with ideas of what to draw is difficult, especially for those who draw on a regular basis. The study participants expressed interest in ways an AI might help them overcome "artist's block" via suggestive or inspirational prompts.

> "That would be interesting if it's something that's randomized your process. So for example, if you're always drawing that thing you have in mind, then it would be fun if something sort of like, messes it up for good."

In addition to exposing the artist to more variety, and creative AI was also seen as a potential time saving device.

> "Because we were speaking about AI, I feel it would be really cool if your tablet and pen could actually learn your patterns as an illustrator. And then when it senses that you're going to draw something, it will be like, 'Are you trying to draw this?' And then you're like, 'yes.' And then it just sort of, based on your usual... Because I feel when we draw faces or something, there's not that much variety. Especially when you draw from your imagination. And then you can just add the edits that you want. But it would be really cool if my tablet could do that for me. It was saved me so much time. And it's still like I drew it. Because basically just it put in there based on all the drawings I've done before."

3. **Artists have a critical and skeptical view on automation of creative work.** Digital drawing tools have already impacted the working practise for artists. Full-time professionals describe how work has changed with the adoption of digital creative tools, such as Photoshop and high resolution digital printing.

> "It's quite sweet when you realise there's something it can do for you, and it can do it in tenth of the time that you do it in. So, in a way, I guess with Photoshop as well it's sort of. There is a bad side to it all. It has basically screwed my career in a sort of way. Because illustrators like me used to be really busy the whole time. Twenty-odd years ago, thirty years ago. Cause we'd have to be paid to do everything. And now, a lot of people do things themselves, cause they think 'oh we've got Photoshop, we can do this. we've got clip art'... "

Some illustrators are aware of the outputs of the computational creativity community with creative AI and advances, such as Google's *Inceptionism* (Mordvintsev et al., 2015). However, artists also share a critical view that these systems are indeed creative in the origination of ideas.

> "I see a lot of imitation [*in the output of creative AI systems*]... something comes out of it, which is cool... sure, it's like still unique in its own way, but it's not... I can't see how they [*AI systems*] were thinking. Or besides the fact that it was really intricately, like spiral drawings that they do. But, then they are probably, using some really crazy mathematical equation or something. But that doesn't spark anything. I'm just like, okay, it's a cool aesthetic. Like it looks really cool, because that's what they did to get to that point. But there was no major concept behind it. There's no reason why they [*AI systems*] did it."

Finally, some professional artists who participated in the study expressed some reservations about contributing to research, such as this study, that could lead to a produce that might eventually threaten their ability to find work as a creative practitioner in the future.

5. OBJECTIVE RESULTS: DRAWING EXERCISES

In this section, we discuss the results and objective analysis of the middle component of the study: the drawing exercises. During each session, we asked participants to engage in three different drawing exercises, which we video-recorded. Our purpose was to observe how participants approach different types of drawing tasks (as outlined in section 3.4):

A. **Observation**—*"Draw a still-life"*
B. **Recollection**—*"Draw a bicycle from memory"*
C. **Imagination**—*"Draw anything"*

Participants were prompted as above for each exercise and asked to complete each drawing within 10 min. The exercises were assigned in the same order (i.e., A, B, C above) for all participants. Due to the exploratory nature of the study, the 10-min drawing time was not strictly enforced, and some participants squeezed in extra finishing touches to their work after the "time's up" prompt was given. For others, the 10-min drawing time was considerably shorter than what they are used to, while others were able to complete the drawing within the allocated exercise drawing time. We labeled the completion status for each drawing as: *early* if they completed their drawing before the 10-min time limit; *done* if they completed their drawing at the 10-min limit or just beyond; and *midway* if they hadn't completed their drawing at the 10-min time limit and did not take extra time to finish.

An example of the sketches produced from the three drawing exercises for a single participant is shown in **Figure 7**. Collectively, the outputs from the drawing exercises comprise a small video gallery that can be viewed side-by-side in various combinations in order to contrast drawing styles across participant types. Each exercise provides a way to see how an individual begins the drawing task, blocking out space, drawing outlines, adding texture and detail. A sped up video showing side-by-side comparisons of different participants types is available as part of this publication[4].

We analysed the drawing exercise video data by examining a range of statistics that describe the time spent on each exercise and characteristics of participants' drawing habits that could be discerned manually. This method was applied to the 63 drawing exercise videos[5] and the results are discussed in section 5.1.

Although not applied directly here, we also considered classic *image processing* techniques for in-depth analysis of video features. Section 5.2 references an exploratory exercise which was conducted on a similar data set (a small sample gathered during pilot testing prior to the user study detailed here) and explains

[4]https://youtu.be/fsf8wskYZdg.
[5]21 participants × 3 exercises.

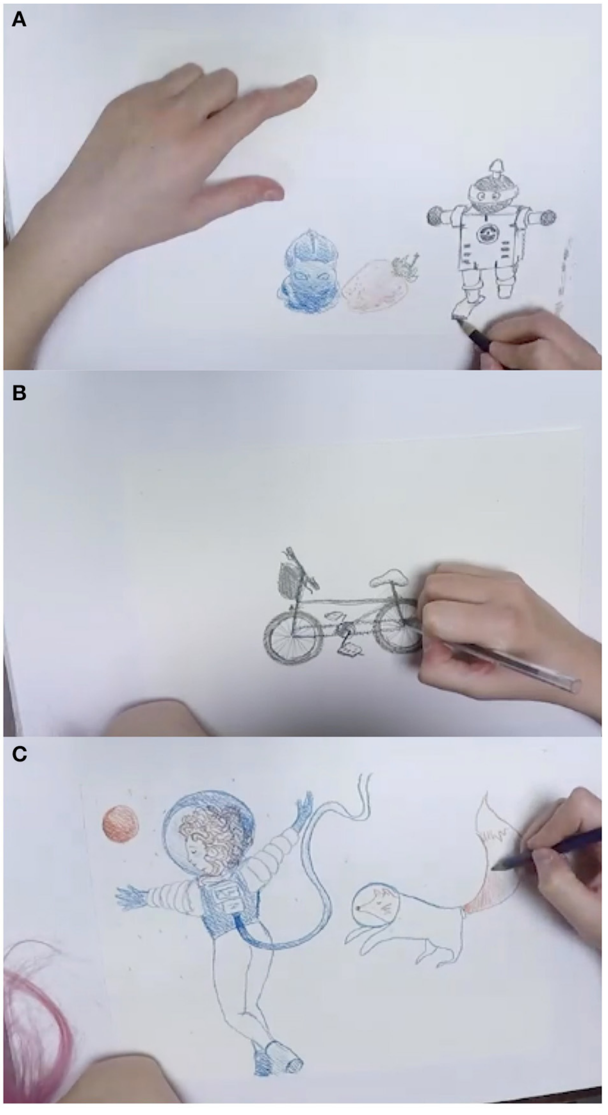

FIGURE 7 | Drawing exercises in progress for a single study participant, showing **(A)** still life drawing, **(B)** drawing from mental image, and **(C)** free drawing.

TABLE 4 | Statistics on time spent drawing for each exercise.

	A Observation	**B Recollection**	**C Imagination**	**Total**
Mean	10:33 (01:15)	08:37 (02:41)	10:08 (01:43)	29:18 (04:10)
Shortest	3	**13**	5	21
Longest	**11**	5	5	21

The first row reports mean and standard deviation (in parenthesis) reported, in minutes and seconds. The second and third rows report the number of instances (out of N = 21) where each exercise took the shortest and longest, respectively, amount of time for a given participant. Bold indicates which of the exercises had the top number of instances for the shortest and longest duration.

how lessons learned from this exercise could contribute to future automated analysis of drawing video.

5.1. Statistical Analysis of the Drawing Videos

Here we examine various statistics descriptive of the drawing exercises. These include: the time taken for drawing, 'handedness" of participants, numbers of pages used per drawing, paper movement, drawing media, and completion status.

5.1.1. Drawing Time

Table 4 illustrates statistics related to the amount of time spent drawing for each exercise. Time is reported in minutes and seconds, with mean and standard deviation in the first row of the table. Although all participants were given the same time window (∼10 min) for each exercise, we were interested to compare the time spent by each participant on each of the three categories of drawing: observation, recollection and imagination. Exercise B (recollection) took the shortest amount of time for most participants (13 or 62%). Exercise A (observation) took the longest amount of time for most participants (11 or 52%). We can loosely conclude that many participants found observation took longer while recollection was faster.

5.1.2. Handedness

From the video, we observed whether participants are left-handed or right-handed with respect to the drawing activities. Approximately 90% of the population overall is right-handed (Peters et al., 2006). In contrast, 81% of the participants in our study are right-handed.

We further examined the timing statistics discussed above with respect to handedness, to determine if right-handed participants were generally faster or slower than left-handed participants; however, no such conclusion is found. So we cannot say anything about the existence of a relationship between handedness and drawing speed based on the data set we collected in this study. Correlations between handedness and other characteristics are considered, in turn, as each additional characteristic is discussed below.

5.1.3. Number of Pages

Most participants only used one page for each of the three exercises, but 6 (29%) participants used more than one page for at least one of the exercises. Nobody used more than one page for all three exercises, so there was no detected consistency with respect to using more than one page. There was also no correlation between handedness and the number of pages used. One primary reason for using multiple pages was that some participants reserved one drawing per page, while others drew small multiples on the same page. For example, in exercise B, some participants had false starts while working out how to draw a bicycle and used multiple pages in the process. One participant worked on many ideas in exercise C, and iterated through many drawing very quickly.

5.1.4. Paper Movement

The paper on which participants drew was placed on the table in a bounded region to ensure that it was visible by the video camera capturing the exercises. Initially, the paper was placed squarely on the table. Inevitably, the paper moves slightly as people draw. But some participants purposely turn the paper while they are drawing. They orient the drawing at a comfortable angle for a drawing operation, such as drawing a straight line, or filling in a space with a texture. Also, at moments in order to assess their work, some participants pull back and view their drawing from a different perspective. The majority of participants (18 or 86%) moved the paper when working on at least one of the exercises. Of these, seven participants moved the paper during all three exercises. Interestingly, all of the left-handed participants moved the paper during at least one exercise; thus all of the participants who did not move the paper are right-handed.

5.1.5. Drawing Media

Participants were permitted to employ whatever drawing media they desired, and we recorded a range of different tools. These are: charcoal (plain, medium or stick), eraser, finger smudge, graphite (or graphite stick), marker (brush, chisel, posca, tombow brush, tombow felt, tombow fine), pastels, pen (ballpoint, gel, micron 0.03, micron 0.05, micron 0.1, micron 0.3, mitsubishi felt 0.05, mitsubishi felt 0.5, pilot felt, pilot uniball, stabilo fine, tombow brush), pencil (2B, 4B, color, HB, mechanical, prismacolor ebony) and watercolors. One participant employed a digital drawing tablet for the free-drawing exercise (exercise C), using an Apple Pencil stylus with the Procreate sketching application. **Table 2** shows the distribution of drawing tool usage across all 21 participants. The most commonly used tools were some form of pencil (employed by 81% of participants), eraser (57%), and some form of pen (57%).

Next we look at the tool usage per artist. Most artists (19 or 90%) used more than one drawing tool for at least one of the drawing exercises. Nine artists (43%) always used more than one tool (i.e., for every drawing). Only two artists only used one tool for each drawing. Interestingly, one of them used the same tool for all three drawings (a 2B pencil), whereas the other used two different tools but did not change between tools during a drawing (prismacolor ebony pencil for exercises A and C, and graphite for exercise B). Again there was no correlation between handedness and tool usage.

5.1.6. Completion Status

As described earlier, we labeled each drawing according to whether the participant finished drawing before the 10-min time limit ("early"), at or shortly after the time limit ("done") or did not complete their drawing ("midway"). **Table 5** shows the distribution of completion status labels with respect to each drawing exercise. For exercises A and C, most people completed their drawing at or shortly after the time limit. For exercise B, most people finished early; indeed, for exercise B, everyone finished. Overall, most people completed their drawings, as only 11 (17%) out of the total number of drawings ($21 \times 3 = 63$) were labeled as incomplete.

TABLE 5 | Completion status for each exercise.

	A Observation	B Recollection	C Imagination	Total
Early	4 (19%)	**13** (62%)	4 (19%)	21 (33%)
Done	**10** (48%)	8 (38%)	**13** (62%)	31 (49%)
Midway	7 (33%)	0 (0%)	4 (19%)	11 (17%)

Bold indicates the top completion status for each exercise.

Looking at the completion rate per participant, we find that 12 (57%) of the participants completed all three drawings. There is no correlation between completion status and handedness, as half of the left-handed people completed all three drawings and half did not.

5.2. Future Opportunities Using Image Processing

The drawing videos provide a rich data set to which a range of automated *image processing* techniques could be applied in order to identify features that might provide insight into different artists' drawing styles. To inform this direction for future work, an exploratory exercise (Kim, 2019) was conducted in which a few *computer vision* and *machine learning* methodologies were applied to a small sample data set comprised of three drawing videos collected during pilot testing for the user study detailed in this article.

This exercise explored automatic identification of features from the sample videos, including: stroke length and stroke speed patterns; hovering habits (i.e., holding the drawing implement poised above the drawing surface); and paper usage, including the amount of a page typically used, the region of the page covered (e.g., top, bottom, middle, left, right portions) and the location pattern, such as starting in the middle and moving out or drawing from top to bottom or left to right. For example, referring to **Figure 7**, one can see that the lower right portion of the paper was utilized for drawing exercises A and B, whereas the entire page was utilized for exercise C.

In order to compute the features listed above, the first step is to detect the location (coordinates) of the endpoint of the drawing implement within each video frame, as well as the length of line(s) drawn between one frame and the next. For example, the endpoint can be seen clearly in **Figures 7A,C** but is obscured by the artists' hand in **Figure 7B**.

The exploratory exercise attempted to automatically classify each video frame as either "hidden" or "not hidden," indicating whether the endpoint was clearly visible or not. Further, each "not hidden" frame was classified as either "drawing" or "not drawing," indicating whether the endpoint of the drawing implement was in contact with the surface of the paper or not (e.g., hovering above the page). These binary classification results, obtained by applying a sequence of classic image processing methods (e.g., edge detection and color segmentation to identify the artist's hand, drawing implement and the drawing artifact itself) followed by comparing various supervised learning algorithms (e.g., decision trees, logistic regression), proved to be slightly

TABLE 6 | Co-creative drawing systems characterized by interaction factors (section 7.1) and actions (section 7.2).

System	Initiative	Synchronicity	Actions	Spatial overlay
Exquisite Corpse Brotchie and Gooding, 1991	Low, turn-taking	Synchronous	Completion	Shared canvas, no-overlay
FluidSketches Arvo and Novins, 2000	High, continuous	Asynchronous	Correction	Shared canvas, replaces drawing
AutocompleteAnimation Xing et al., 2015	Low, on request	Synchronous	Transformation	New drawing
ShadowDraw Lee et al., 2011	High, continuous	Synchronous	Suggestion	Shared canvas, overlay (underlayer)
Drawing Apprentice Davis et al., 2016a,b	Adjustable, continuous, turn-taking	Asynchronous, synchronous	Improvisation, trace, transformation, imitation	Shared canvas, overlay
DuetDraw Oh et al., 2018	Adjustable, continuous	Asynchronous	Completion, transformation (colorize)	Shared canvas, overlay
Creative Sketching Partner Karimi et al., 2019	Low, on request	Synchronous	Conceptual shift	Separate, adjacent canvas
collabdraw Fan et al., 2019	Low, turn-taking	Synchronous	Completion	Shared canvas, in-place
DialogCanvasMachine Cabannes et al., 2019	Low, turn-taking	Synchronous	Suggestion	Shared canvas, overlay
D.O.U.G. Chung, 2015	High, continuous	Asynchronous	Imitation	Shared canvas, overlay
ArtTherapyRobot Cooney and Menezes, 2018; Cooney and Berck, 2019	Low, turn-taking	Synchronous	Imitation, visual metaphor	Shared and separate canvases, overlay

more accurate than random (between 50 and 60%) at predicting the correct labels for a given frame. However, a substantial amount of customized pre-processing of the data was required, in particular manually labeling enough video frames for training the supervised learning algorithms.

For frames classified as "not hidden" and "drawing," it is then possible to compute the location of the endpoint of the drawing implement. This can be interpolated to an (x, y) coordinate within imagined axes that run along the edges of the drawing surface (page). Depending on where the endpoint is, some skew in this coordinate system may occur in the video frame; and this skew needs to be eliminated in order to reduce the noise that arises in trying to correlate series of (x, y) coordinates in consecutive video frames. Similarly, for consecutive frames classified as "not hidden" and "drawing," the change in (x, y) coordinates can be mapped to interpolate a drawn line. An initial plan for finding the drawn line by calculating the difference between two consecutive images proved to be too noisy, largely due to the movement of the artist's hand. For example, even if the artist does not draw from one frame to the next—e.g., they lift their hand and drawing implement above the page—the shift in hand can obscure the line just drawn and confuse the drawn line detection method.

This exploratory exercise revealed a number of challenges that would have to be resolved before automated analysis of drawing video could be effective: (1) the raw video frames need to be cropped to remove noisy regions beyond the borders of the paper on which the human participant is drawing (e.g., around the edge); (2) many frames need to be labeled in order for an algorithm to learn to locate the endpoint of a drawing implement accurately within a video frame; (3) skew needs to be eliminated in calculating drawing implement endpoint accurately; and (4) significant sources of noise further confound automated video, including variable lighting conditions, occlusion of the drawn line by artist's hand and similar occlusion of the drawn line by the artist's drawing implement. The first two challenges involve manual processes that can be very time-consuming. Finally, the learned results obtained in this exploratory exercise were not very accurate, though better than random and may warrant further investigation.

6. APPLYING THE RESULTS

As mentioned in the Introduction (section 1), the outcomes from this user study contribute to the development of our prototype system for enabling AI-based collaboration in co-creative drawing practice. In this section, we identify a set of design requirements and a set of technical specifications for our prototype, generated from analysing the user study data. Finally, we describe our current demonstration system, explaining how the recommendations resulting from the user study are realized through technology.

6.1. Design Requirements for Co-creative Drawing System

The user study presented here suggests the following set of design requirements for our prototype system following directly from the thematic analysis described in section 4.2.3:

1. **Drawing Physically.** Artists employ a range of different types of drawing implements (see **Table 2**). We want our prototype to allow the artist to draw in a similar manner as was done in the user study, with their choice of physical media. The aim here is to maintain direct tangible interaction with the physical media as much as possible.
2. **Integrate Drawing Texture.** Video from the drawing exercises exhibited a varying range of textured outcomes from how an artist uses physical media (see section 5.1.4). We want our prototype to integrate the resulting texture from physical media into the way that the system observes the evolution of a drawing.
3. **Maintain Editorial Agency.** We want the artist to maintain primary editorial control with what is actually drawn (see section 4.2.2). This design criteria means that instead of having a drawing AI or robot modifying the art piece, the artist ultimately has the control as to what is actually drawn on the piece. Interactions with the drawing AI is more passive, where the artist is reacting to phenomena that the system presents as opposed to the system modifying the artwork itself.

6.2. Technical Specifications for the Research Prototype

We have identified a set of features for setting technical specifications that our prototype system should meet. These are listed and described below.

- **Spatial Resolution.** The spatial resolution of the input components dictates the fidelity the system is able to capture the drawn lines. For example, the study's video was recorded at a resolution of $1,920 \times 1,440$ pixels. Assuming, perfect framing of an A4 sheet of paper (297×210 mm), the resolution is 6.4–6.8 pixels/mm. However, in practise the drawing surface typically occupies about a 1/3–1/4 of the image, so this resolution is 2–3 pixels/mm. In contrast, a commercial drawing tablet captures a resolution of 100 points/mm.
- **Temporal Resolution.** Temporal resolution dictates how often the system can capture the incremental progress of the drawing process. This is a function of the data-capture frequencies of the input components. For instance, the video recordings of the drawing exercises occurred at 25 Hz, which from our initial image analysis (see section 5.2) provides a coarse capture of drawn lines. In contrast, commercial drawing tablets digitize pen positions at 200 Hz, which provides higher resolution detail of how lines are drawn. Another consideration with temporal resolution is the case where multiple input components are used. In this case, data captured at different frequencies will have to be correlated to each other temporally.
- **Baseline Responsiveness.** Physical media is as lively as physics allows. Because of this, the system should be as responsive as possible to physical drawing. There is a minimal latency for when the artist makes a mark and the system is able to respond on the drawing surface. A baseline response time of under 0.1 s is necessary for the sense of instantaneous reaction from the system (Nielsen, 1994).
- **AI Processing Time.** In addition to the baseline response time, the system's AI requires processing time. The amount of time the system has to process input and render an output dictates how sophisticated a response is possible. For instance the Javascript implementation of the *sketch-rnn* model (Ha and Eck, 2017) can process a generating vector drawings within 1/60-th of a second and maintain interactivity. There is trade-off between the speed and frequency of the system's response and the processing time allocated to the AI while remaining responsive.
- **Resilience.** Individual components will experience noise and disruption as part of their input processes. Occlusion of the drawing activity by the artist's body and by other objects placed on the drawing surface was a major issue identified in the analysis of the drawing exercises (see section 5.2). Lighting conditions impact the quality of image capture through shadows, flickering from light sources and reflections off the artist's body and accessories (e.g., eyeglasses, metal jewelery). While one can mitigate the setting in which the system operates in experimental lab conditions, for operation "in the wild" (e.g., the artist's studio), its components would require larger tolerances on the input data.
- **Endurance.** The research system would have to maintain the throughput and be able to manage the volume of data from a typical drawing session. At a minimum, the research system should be able to sustain operating through three 10-min drawing sessions that were executed as part of the pilot study. However, we know, from the survey (**Q9**, **Figure 4**), most artist's working time is between 1 and 2 h per session. The single camera from the drawing exercises recorded 1 Gb of video for every 4.5 min. Even if the video is processed, at the early stages of the development of the research system, one would anticipate storing high fidelity video of the drawing session for offline processing and training.

6.3. Technical Set-Up of Prototype System

With the technical considerations from section 6.2 in mind, we have developed an early version of our prototype system. **Figure 8** shows an image of the prototype (*left*) and corresponding schematic design of its components (*right*). Each component is controlled by a dedicated Raspberry PI[6] coordinated through a distributed messaging framework that is commonly used in robotics and autonomous systems research, namely the Robotic Operating System (ROS)[7]. The sensing components are: three Raspberry PI v2 cameras[8] ($\mathbf{C_{TOP}}$, $\mathbf{C_{LEFT}}$ and $\mathbf{C_{RIGHT}}$), an Intel RealSense SR305 depth camera[9]

[6]https://www.raspberrypi.org.
[7]http://ros.org.
[8]https://www.raspberrypi.org/documentation/hardware/camera/.
[9]https://www.intelrealsense.com/depth-camera-sr305/.

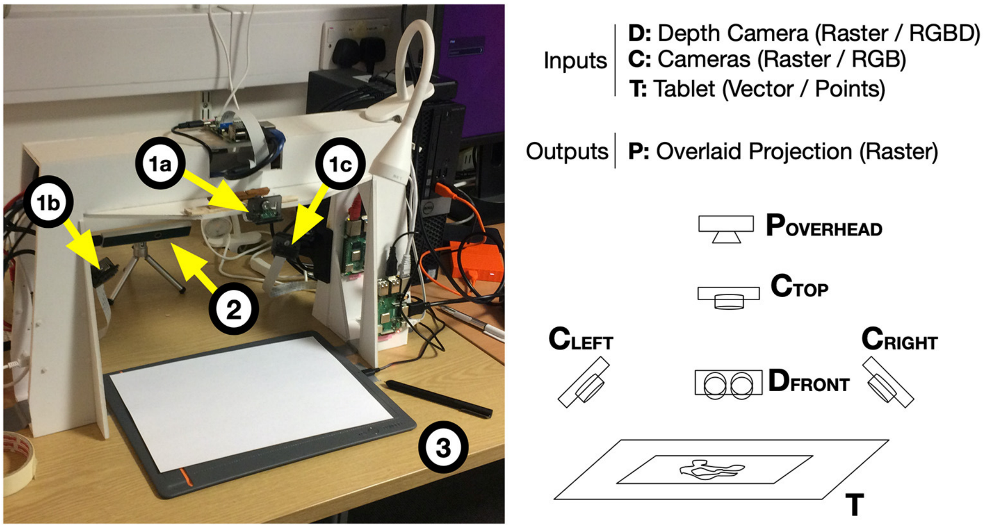

FIGURE 8 | (Left) Design of prototype research system with Raspberry PI cameras **(1a–c)**, depth camera **(2)**, and WACOM Bamboo Slate digital "sketchpad" **(3)**, each with a dedicated Raspberry PI communicating via ROS (http://ros.org). **(Right)** Schematic for prototype research system.

(**DFRONT**), and a WACOM Bamboo Slate[10] digital "sketchpad" (**T**), which uses a pressure sensitive pen that tracks movement and produces marks on physical paper. The cameras observe the drawing area from multiple angles and record textural aspects of the drawing, while the digital sketchpad records a vector representation of the pen's movements.

Our design includes a projector **POVERHEAD** which overlays the robot's interaction upon the drawing surface and will be utilized in a future study. Through the use of projection, as the AI's only mode of output, the human artist maintains sole physical agency to manipulate the physical drawing in progress.

7. DISCUSSION

This section discusses the results of the user study in light of related work (see section 2) and considers how might one categorize a collaborative drawing AI. Section 7.1 compares the outcomes from the user study in categorizing a drawing AI in terms of how it interacts with an artist. Section 7.2 discusses various actions that the AI might take in a co-creative drawing process and compares existing co-creative drawing systems from section 2.4 within this context. Section 7.3 looks at how the outcomes from the user study impact the ongoing design of our prototype system.

7.1. Interaction Factors

We identified a set of factors indicating how an AI might interact during the artist's process. **Table 6** characterizes the related co-creative drawing systems in terms of the interaction factors and actions discussed in this section. They are:

1. **Synchronicity** *Synchronous* drawing means that the artist and the AI are taking turns drawing onto the piece one at a time. Turns may alternate, or one actor may take the *initiative* (see below) to take multiple turns in a row, without waiting for or requesting permission from the other. In synchronous mode, the notion of *turn* must be defined so that each actor can signal to the other that they have completed their turn; or turns could be based on fixed lengths of time (e.g., 5 min each). *Asynchronous* drawing is where the artist and the AI draw at any time, independently of each other. In this case, the AI and the artist may draw with varying initiative.
2. **Initiative** Initiative describes the level of autonomy given to the AI for interacting with the drawing. A system may have high initiative, in which case the AI will be more likely to contribute to the drawing on its own accord (i.e., without waiting for the artist to request assistance). In contrast, a low initiative AI may be required to wait for a prompt from the artist before it can contribute to the drawing. The level of initiative might be set by the artist, such as in the *DuetDraw* (Oh et al., 2018).
3. **Spatial overlay** This refers to where the artist and AI are drawing with respect to each other. Their drawing canvas may be *shared*. In this case their drawing interactions might *overlay* each other or occur in separate regions on the canvas from each other. This could be defined ahead of time by the artist or by the AI, or by some negotiation process before drawing starts. This could also be re-negotiated during the drawing process. The flexibility of this factor will be constrained by the physical limitations of the prototype system (e.g., the human artist can take their pen and go over to a random wall and start drawing, but the AI will only be able to sense and respond within the regions accessible to the system's cameras and projector).
4. **Actions** An AI will take one or more actions to collaborate with the artist. Through the user study and from reviewing related co-creative drawing systems we compiled a

[10]https://www.wacom.com/en-us/products/smartpads/bamboo-slate.

non-exhaustive list of these actions which are elaborated further in section 7.2.

7.2. AI Actions

In this section, we describe a range of actions that AI might take while an artist is drawing. These are based on an analysis of the works described in section 2 and the themes from the artists' interviews (section 4.2).

7.2.1. Correction

An AI might *correct* the artist's drawing according to specific model of drawing. For instance, the *FluidSketches* system (Arvo and Novins, 2000) identifies drawing primitives in the artist's drawing and converts them to idealized geometric primitives. This form of AI action was a common theme that came up in the interviews, and often the artists saw this as something useful for learners but not necessarily for themselves (see Key Theme 2, in section 4.2.3).

7.2.2. Tracing

An AI might *trace* over what the artist is drawing, which is a strategy in the *Drawing Apprentice* system (Davis et al., 2016a,b). Conversely, an artist might utilize tracing as feedback to the drawing AI, reinforcing the drawn strokes as desirable, or to signal a correction to the AI. The concept of the tracing action did not come up in the artists' interviews. However, what did surface was a desire for digital art programs (e.g., Photoshop) to perform better *vectorization*, or converting a raster scanned image into discrete vector art.

7.2.3. Imitation

A less strict strategy to tracing is to *imitate* what the artist is drawing. This can occur both on the same canvas, as with the *D.O.U.G.* robotic drawing system (Chung, 2015), or on a separate canvas as with the *ArtTherapyRobot* (Cooney and Menezes, 2018). In the interviews, imitation did not come up as a possible AI action. However, there was a concern as to whether the artist has the copyright with respect to AI generated imagery.

7.2.4. Suggestion

An AI might *suggest* to the artist what to draw next based on its model of the artist's drawing process. An AI which operates like Microsoft's *Clippy* digital assistant would suggest something for the artist to draw, and the artist would approve or reject the suggestion. Instead of seeking approval, the AI could be continually suggesting something to draw, in the manner of *auto-complete* predictive text interactions. The *DialogCanvasMachine* (Cabannes et al., 2019) suggests drawn strokes in the form of a projection onto a physical canvas. The artist draws their interpretation of the projected drawing onto the canvas. The *ShadowDraw* (Lee et al., 2011), instead of explicit drawing, displays gradient of drawings suggestive scaffolding which the artist can draw over. Suggestion of what to draw, as a result of the AI predicting what the artist might draw next, was a strong theme in the interviews. Creative autonomy was important for the artists, and some saw having the AI suggest the next stroke as getting in between them and their drawing (again, see Key Theme 2, in section 4.2.3).

7.2.5. Improvisation

An AI might be like an *improvisational* partner contributing to a drawing according to its own drawing process without suggesting anything to the artist. This improvisation could be reactive to what the artist is drawing, such as with the *Drawing Apprentice* system (Davis et al., 2016a,b). Improvisational actions taken by the AI were proposed as a concept by the interviewer, however conceptually it was difficult for artists to see how *visual* collaboration might occur. One artist discussed their use of improvised drawing games as part of a workshop for drawing for children (e.g., each person taking turns adding a stroke to a composition).

7.2.6. Completion

An AI might *complete* a drawing for the artist. This completion might be based on an explicit model that the AI uses of the drawing, such as the animal categories in the *collabdraw* system (Fan et al., 2019). It may attempt to identify and complete what the artist is drawing as in the *DuetDraw* system (Oh et al., 2018). The *DuetDraw* system also allows the artist to have the AI *colorize* the drawing, which is a form of completion as well. The AI might complete the drawing according to its own model in the manner of the parlor game, *Exquisite Corpse* (Brotchie and Gooding, 1991), in which participants take turns to contribute to a drawing without visible knowledge of what the other person is drawing, producing a novel surrealist outcome. Completion did come up as a theme in the interviews, in particular as a labor saving device for completing aspects of a composition, such as background rendering or texturing (see discussion in section 4.2.2).

7.2.7. Transformation

An AI might *transform* what the artist has drawn in a different style, which is used in the *Drawing Apprentice* (Davis et al., 2016a,b) and the *DuetDraw* (Oh et al., 2018) systems. Transformation assumes a form of replacement of the drawing in contrast to completion which is additive to the drawing. In the *AutocompleteAnimation* system (Xing et al., 2015), the AI produces the next frame in an animation series based on previous drawn frames. One might think of this process as transformation of a drawing into its consecutive frame. This concept of automating this *tweening* process did arise in a discussion for the labor-saving contributions of an AI collaborator.

7.2.8. Conceptual Shift

An AI might inspire an artist by providing a *conceptual shift* in what they are drawing. The *Creative Sketching Partner* (Karimi et al., 2019) displays reference imagery that is visually similar but semantically is different to what an artist is drawing. In this case the AI is not contributing drawn strokes to the artist work, but is showing a reference. This concept of having the AI evaluate what the artist is drawing and searching for similarity within some knowledge base did come up in the interviews. In particular, there was a desire to see how novel what one is drawing, and to have the AI evaluate the originality of the work.

7.2.9. Visual Metaphor

An AI might contribute to that artist's drawing based on a *visual metaphor* of a sensed emotional state in the artist, which is utilized by the *ArtTherapyRobot* (Cooney and Berck, 2019). This theme of visual metaphor and sensing the emotional state of the artist did not come up in the interviews.

7.3. Impact on the Design

In this section we discuss open questions which arose as a result of the user study and how they impact the development of the prototype system.

7.3.1. How Can the AI Reason About Spatial Aspects of the Drawing Process?

There are two dynamic systems happening simultaneously which are related in the sense of where the drawing tools touch the surface.

First, there is the movement of the artist's body, their arm, their hand, the drawing tool, the tip of the tool as it approaches and touches down varying in pressure and movement, and leaves the drawing surface. There is a spatial strategy to how an artist draws. And the movements are different from how a machine, such as a pen plotter printer, would render an image. Robotic drawing systems, such as *The Painting Fool* (Colton, 2012), are programmed explicitly to follow an artist's style of movement as opposed to that of the plotter. Having a richer understanding of the dynamics of the artist's body can enrich the development of such systems.

Second, there is the evolution of the drawing artifact itself as a dynamic system. From our analysis of the drawing exercise videos, artists drew a lot but erased little. Most of the time the drawing was "additive," which means that it grew with respect to spatial coverage of the drawing surface. Indeed, some erasures are additive in themselves, in the form of added marks, smudges, and/or smears on the surface.

Thus, we can also explore spatial analysis approaches to the evolution of the drawing. Measuring the spatial arrangement of points through *point-pattern analysis* and *density estimation* (de Smith et al., 2018) would provide information about "where" an artist is drawing and "when." For instance, a heat map over time, indicating where on the page the "hot area" is (i.e., where the artist is currently drawing) vs. "colder" areas that are older in the drawing timeline, would provide user information for a co-creative partner to either avoid disturbing the artist by drawing in the same area or to intervene where the artist is actively drawing.

7.3.2. How Might Artist Fatigue Influence System Interaction?

Fatigue is real, for artists, but not so for machines, at least at the scale of a drawing session. Drawing is a physical activity, even on digital devices. There is a warm-up period, a period of performance and then onset of fatigue. It may be possible to measure this physical cycle within the dynamics of the artist drawing, and have the co-creative AI consider and respond to fatigue within a drawing. With the exception of the *ArtTherapyRobot* (Cooney and Berck, 2019), which models the emotional state of the artist, the existing co-creative drawing systems are "robotic" and not empathetic (i.e., generally not responsive to changes in the user's behavior).

7.3.3. How Does the Drawing Medium Impact Digital Image Representation?

Drawing acquisition from a camera input is a research challenge. Cleanly acquiring the drawing, segmenting it from the background of the drawing surface and converting it into a vector representation is a research challenge. Existing systems that work with physical media utilize bold painted lines, such as the *DialogCanvasMachine* (Cabannes et al., 2019), to produce a high contrast image. From our survey, pencil is the most common medium for drawing, and may leave very light marks on paper which may be difficult for a camera to pick up. However, another outcome from the survey was that the physical-to-digital workflow is more typically from a drawn image on paper into Photoshop, and the artist would work on drawing at the pixel level. Only when they required scalable or crisp line-work, did the artist vectorize their drawings. If the novelty of drawing with analog media is maintaining a rich texture, then a co-creative drawing system might work at the pixel-level instead of initially vectorizing the drawn input. Such a trade-off would require the prototype research system to have a richer representation of the drawing, rather than the common vector points-and-strokes object model.

7.3.4. How Could an AI Interact With an Artist?

Having the AI interact with the drawing surface that is clear to the artist is an interface challenge. The AI could draw or have their interactions presented on a separate canvas or screen. However, this loses the immediacy that having the artist and the AI share a common drawing surface. One of our primary design requirements (see section 6.1) is to allow the artist to draw upon a physical surface. In this case, the AI could have a robot drawing on the surface, like in the *D.O.U.G.* system (Chung, 2015). Another design requirement is maintaining editorial control, so having the AI drawing physically as well is not practical. In this case there are two manners in which the AI could interact with the drawing.

First, it could use projection, as is done with the *DialogCanvasMachine* (Cabannes et al., 2019). Projection is non-destructive to the drawing, as opposed to having a robot draw upon the surface as well. Another advantage is that projection allows a large variation in options for drawing surfaces. Thicker materials, such as canvas, boards, and walls are eligible surfaces in this sense. However, there are trade-offs with projection. One primary obstacle is that occlusion of objects in front of the projection casts shadows onto the surface. Shadows cause sharp contrasting shapes upon the surface which and that may confuse camera input of the drawing. Projection also is sensitive to lighting conditions. Many participants desire drawing in brighter lighting conditions with natural light. A projection could provide more of this lighting. However, the contrast of the projected imagery risks being washed out under bright lights.

An alternative method is to project underneath the drawing surface. This is similar to the light-box set-up wherein a light source located underneath the drawing surface shines upwards and allows the artist to trace imagery onto thin media, such as light weighted paper. In this case, the paper would need to be thin enough to project through. Such an effect could also be produced through the use of a strong (bright and high-resolution) monitor as the drawing surface (e.g., a digital display table).

7.3.5. How Could a Co-creative AI-Based Drawing System Introduce Artists to Collaborative Drawing?

Collaborative or collective sketching activities were rare amongst most participants of our user study, especially amongst part-time and students (see sections 4.1.2 and 4.2.2). In addition, most people interpreted "collaborative drawing" as attending life-drawing classes and looking at each other's drawings. Only one participant described having participated in a collaborative drawing activity where more than one individual drew on the same piece of work. This lack of collaborative drawing experience might be a novel opening for them working with a collaborative drawing system, with less preconceived notions toward collaborative drawing. In fact, the interview discussion in the study might have had an impact on the artist's practise in opening their eyes to collaborative drawing practice. Finally, it is likely for future participants that using our research prototype might be their first collaborative drawing experience,

8. SUMMARY AND CONCLUSION

This article has presented the results of a user study of drawing practitioners, conducted with the objectives of understanding their drawing practises and workflow and discussing their thoughts on collaborative drawing with an AI-supported system. The study gathered survey data, videos of drawing exercises and transcripts of interviews discussing artists' working habits and ideas around a co-creative drawing AI. Having the analysed the data, we have identified some key themes, design criteria and technical specifications for a prototype co-creative drawing system, and then presented a technical set-up of our current demonstration version of the system. We connected our analysis to related work in the literature, suggesting potential activities and characteristics for a co-creative drawing AI.

In closing, we mention lessons learned through developing, delivering, and analyzing the user study (section 8.1) and identify possible avenues for future work to come out of this study (section 8.2).

8.1. Lessons Learned

This section highlights a few of the key lessons we learned about the design of our user study from its delivery and analysis of the data gathered.

8.1.1. Survey

The survey could have been improved to better extract specifics about an artist's drawing practise. The participants are overall passionate about drawing, so to ask "How long have you been drawing?" often just has them expressing their age, or an answer to the effect of "I've been drawing my entire life." However, we were seeking something more specific about how much experience they had with drawing at a more serious capacity. There might be more specific ways of asking about experience than just asking for the number of years that they have been drawing.

Some participants struggled to characterize their typical working session. In particular, they found it difficult to assess how long a working session is, as there is variation in the time they spent working. This might be best broken up into a few questions. For example, we could have asked: "What is the shortest, the longest and the typical duration of a working session for you (or that you would consider a working session)?" Or, we could also have asked directly: "How do you define a working session?"

The survey also presented a laundry list of qualities of artists' work environments (**Q12**, see section 4.1.5). Some of these were related to each other in that they expressed opposing qualities (e.g., "Noisy environment" vs. "Quiet Environment") while others were unrelated. We could have grouped these environmental qualities into more specific questions with ranges that inquire directly about factors, such as noise level, light level, public vs. private, and solitary vs. shared settings. Also, the context for this question could have been expressed more clearly as it was ambiguous whether we were referring to their *current* drawing environment or their *desired* drawing environment.

8.1.2. Drawing Exercises

The video capture of the drawing exercises was very informative with regards to technical challenges of capturing image data of the drawing process. Lighting conditions in an academic office environment are generally poor for studio work. Fluorescent lights caused undesirable flickering. For the first half of the participant settings, the camera capture frequency was incorrectly configured (i.e., set to NTSC where the setting should have been PAL).

While the top-down egocentric camera view gives the best overview of the drawing area, much of the drawing actions were blocked by occlusion (see section 5.2). Given the choice of having only one camera, either a top-down from the side (opposite the handedness) or oblique from the top of the drawing surface would have captured more of the drawing actions.

There's a balance between wanting to set up the drawing environment so as not to distract the artist (i.e., a "natural" setting) vs. aiding in the technology-based capture of the artist at work. We allowed the artist to rearrange the drawing environment to suit their needs. However, having a consistently positioned drawing surface by affixing paper with tape would aid in the post-processing for analysis. In addition, when switching pages, moving the old drawing off camera and presenting a new clear surface would help with analysis, as some of the participants left previous drawings on top of the new drawing surface. But, given that the aim of this study was to understand how artists draw, adding more constraints would have limited our ability to capture the variables that a system deployed "in the wild" would have to accommodate.

8.1.3. Interview Discussion

The interview discussions varied greatly in length despite planning the time for discussion to 30 min. Typical interviews lasted 1 h, and most of the time was spent on the first topic of their drawing practise. Artists had much to say about their work. However, even with breaks, this was a long discussion, and by the time the topic of collaborating with an AI arrived, interview fatigue often had kicked in. Given that obtaining views from artists on this question was one of our primary goals of the study, a more direct structure would have been to present the concept of collaborating with an AI earlier in the interview, and then to have more in-depth discussion about their work in relation to what an AI might be able to contribute.

8.2. Future Work

The open questions presented in section 7.3 mentioned avenues of future work within the context of the design of a co-creative drawing system. Modeling the dynamic movement of the artist's body, applying spatial analysis techniques to the evolution of a drawing, creating empathy models for an AI to use to respond to fatigue as the artist works are areas of research in enriching an AI's understanding of the drawing process. Improving the drawing acquisition workflow of physical mediums, such as pencil drawing, is another area of possible computer vision research area which might make an impact on artists' physical-to-digital conversion workflow. Through multiple cameras or an active camera mounted on a robot arm, higher resolution and more detailed images of the drawing surface are possible. Another area of research is how the AI's drawing is displayed onto the drawing surface. Similarly to the camera set-up mentioned previously, utilizing multiple projectors or a robot-mounted projector might improve the image quality of the projected overlay over the drawing surface. Most of the artists interviewed did not have any experience with collaborative drawing (in the sense we define it for our co-creative AI system). One direction for future work would be to conduct a follow-up study in which we specifically seek out participants who have experience with collaborative drawing and elicit information from them to influence the design of our prototype.

Our next steps with this line of research involve completion of our prototype system, expanding on the demonstration described in section 6.3, constructing and integrating computational models of artists' drawing processes based on some of the quantitative metrics discussed in sections 4 and 5, and conducting a follow-up user study to evaluate the efficacy of our prototype system.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because ethical clearance was given only to publish the research outcomes for the user study. Requests to access the datasets should be directed to CJ, chipp.jansen@kcl.ac.uk.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Research Ethics Office of King's College London as Low Risk Research, approved by the university's Biomedical & Health Sciences, Dentistry, Medicine and Natural & Mathematical Sciences Research Ethics Subcommittee. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

Both authors contributed toward the design of the user study, as well as writing and approving this work for publications. CJ conducted the user study, interviews, and collected the results for analysis and conducted the rest of the analysis present in this paper. ES conducted the statistical analysis of the drawing videos.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frobt.2021.577770/full#supplementary-material

[11] http://roboticart.org/icra2019/.

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Robot Art, in the Eye of the Beholder?: Personalized Metaphors Facilitate Communication of Emotions and Creativity

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Socially assistive robots are being designed to support people's well-being in contexts such as art therapy where human therapists are scarce, by making art together with people in an appropriate way. A challenge is that various complex and idiosyncratic concepts relating to art, like emotions and creativity, are not yet well understood. Guided by the principles of speculative design, the current article describes the use of a collaborative prototyping approach involving artists and engineers to explore this design space, especially in regard to general and personalized art-making strategies. This led to identifying a goal: to generate representational or abstract art that connects emotionally with people's art and shows creativity. For this, an approach involving personalized "visual metaphors" was proposed, which balances the degree to which a robot's art is influenced by interacting persons. The results of a small user study via a survey provided further insight into people's perceptions: the general design was perceived as intended and appealed; as well, personalization via representational symbols appeared to lead to easier and clearer communication of emotions than via abstract symbols. In closing, the article describes a simplified demo, and discusses future challenges. Thus, the contribution of the current work lies in suggesting how a robot can seek to interact with people in an emotional and creative way through personalized art; thereby, the aim is to stimulate ideation in this promising area and facilitate acceptance of such robots in everyday human environments.

Keywords: socially assistive robotics, robot art, affective robotics, robot-assisted therapy, human-robot interaction, social robotics, artificial emotions, artificial creativity

1 INTRODUCTION

The current article proposes that social robots will follow the path of smartphones in becoming prevalent, once they too appear to provide various forms of value at reasonably low cost (hereafter referred to as the "smart phone hypothesis"). This will involve helping not just with everyday tasks and emergencies, but also with fulfilling our social needs, to help us to flourish (e.g., (Fitter and Kuchenbecker, 2018; Block and Kuchenbecker, 2019; Nakagawa et al., 2020)). In particular, social needs for affection and self-fulfillment strongly involve emotions and creativity (Maslow, 1943), which have been described as "final frontiers" in artificial intelligence (Picard, 1995; Colton and Wiggins, 2012). (Some might argue that it would be impossible for robots to engage in such

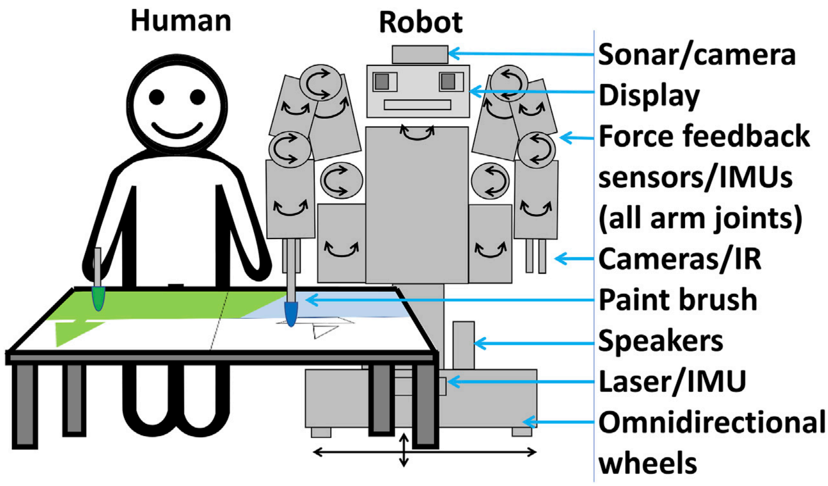

FIGURE 1 | Basic concept. A social robot could interact with people in emotional and creative contexts such as art-making, that provide enjoyment or therapeutic value, given some strategies for personalization and expression through art.

TABLE 1 | Some definitions of terms used in this article.

Socially assistive robot	An embedded computing system, comprising sensors and actuators which afford some semi-autonomous, intelligent, or human-like qualities, intended to interact to support people's well-being
Well-being	A subjectively perceived state, related to happiness, life satisfaction, and quality of life, encompassing physical, psychological, and social factors (hedonic and eudaimonic), and linked with positive emotions and creativity
Emotion	A complex psycho-physical process involving cognitive appraisals, subjective feelings, somatic symptoms, and affect displays, related to sentiment and mood. (Emotion is typically encoded in a simplified manner via dimensions or categories in computers ("the affective gap"); one important interactive form of emotion is empathy, the capability to demonstrate recognition of and caring for another's emotions, which relates to "emotional contingency" or emotional relatedness.)
Creativity	A way of operating characterized by novelty, not something one has or doesn't have (Gershgorn, 2016)
Personalization	A process of adapting to a target, also referred to as customization or tailoring, which has been observed to have positive effects on engagement and trust (Sillence et al., 2006), especially in areas where people are highly different
Symbol	Some representation of a concept, person, or thing. (Here the term does not refer to symbolic art, which was a reaction against realism.)
Abstract	Nonrepresentational, in the sense that people and objects cannot be clearly discerned–rather the art uses shapes and colors to evoke impressions

interactions, as emotions and creativity are human traits; here, an alternative perspective is adopted, that these terms refer to observable "processes," rather than traits that someone or something might or might not possess. Moreover, considering the growing number of artificially intelligent systems targeting applications that were previously thought to be restricted to humans–from complex games like "Go" to writing, composing, and depicting–it seems possible that this line of research could one day affect how we think about ourselves [e.g., if emotions and creativity can no longer be used as a differentia specifica for humans, what might be next for Plato's "featherless biped" (Hodges et al., 2010)?).) Here we focus on one such emotional and creative activity that people of all ages and cultures can enjoy, art-making; painting together with others can positively affect a person's restfulness, self-image, stress tolerance, and vital signs–facilitated by processes of self-exploration, self-fulfillment, catharsis, and self-categorization (Stuckey and Nobel, 2010). From a therapeutic perspective, such interactions with robots could also help to alleviate the rising shortage of human caregivers and growing problem of persisting loneliness, which has been linked to high costs and ruinous health outcomes, and is being exacerbated by isolation caused by COVID-19.

To get started in this complex and challenging scenario, a basic outline of the design space was required: A primary concern was to identify norms and underlying "codes" that could provide value for various users–but personalization was also deemed to be important, as somaesthetic experiences like art-making are highly idiosyncratic (Kerruish, 2017). Furthermore, art can take various forms, such as representational or abstract, which could be perceived differently. Therefore, the goal of the current article was to gain insight into the basic "lay of the land" for how to design a socially assistive painting robot, including such perspectives on personalization and art form; the basic concept is illustrated in **Figure 1**, and some definitions are also provided in **Table 1**.

To address the goal, a speculative prototyping approach was adopted, combining the insights of both engineers and artists, to derive a theoretical design and practical implementation, which could be checked and refined via a small user study: Speculative design facilitates the formation of concrete ideas and problem detection in expansive, ambiguous design spaces (Dunne and Raby, 2013). An exploration solely by artists might have trouble in building the robotic recognition and behavioral capabilities required for interaction, whereas engineers might lack crucial insight into how to communicate effectively through art. Likewise, purely theoretical studies can miss identifying real world challenges, and practical implementations require grounding in ideation to be relevant; for this, "mid-fidelity prototyping" was used to balance speed of investigation with accuracy of insights. Thus, the aim was not to build a finished product or to reveal detailed behavioral mechanisms through rigorous experimentation. Rather, the contribution of the current work lies in exploring this highly complex scenario involving emotions, creativity, robots, and art, and reporting the questions and challenges that arise, toward stimulating discussion and informing next steps in this promising area, as part of an ongoing, larger effort.

The remainder of this article is organized as follows: **Section 1.1** discusses some related work, identifying gaps related to general art-making strategies and personalization approaches; in particular, two basic categories of robots are identified, based on how much their art is influenced by the behavior of interacting persons. **Section 2.1** describes an interaction design derived from our collaborations with artists that strives to balance perceived emotions and creativity, from both theoretical and practical perspectives. How people perceive the design was explored in a small user study with a survey, described in **Section 2.2**. Then, various quantitative and qualitative results are presented in **Section 3** and discussed in **Section 4**, along with ideas for next steps.

1.1 Related Work

The idea of robots that can make art has long fascinated (Herath et al., 2016), and interest in robot art has been growing recently, also as a means to explore new ways of thinking about interactive robots (St-Onge, 2019). For this, collaborations between artists and engineers have been observed to have positive synergistic effects (St-Onge et al., 2011). Some ongoing work has even involved the first testing of an art-making robot at a hospital, resulting in some positive initial feedback (Herath et al., 2020). The design of such interactions could be enriched through insight into general robot art-making strategies and personalization approaches.

1.1.1 General Strategies

Many art-making robots have been created by artists and engineers, for various audiences to see or interact with; here only a few examples can be described. Robot morphologies are diverse, comprising robot arms, as well as humanoid, vehicular, flying, and even animal-like robots (e.g., "Picassnake" (Seo and Young, 2017)). One commonality is that typically some kind of "seed" is selected to guide the robot's art; whereas humans continuously gather rich, multimodal information through complex interactions over long periods, that can be used to inspire art, current robots tend to make art based on more limited data, rulesets, and capabilities. As well, two common kinds of art-making strategy can be described as interactively "exogenous" or "endogenous": Exogenous robots are tools that are dependent on humans to control them, such that some physical human signal like motion or sound results in some physical motion by the robot, allowing human creativity to be directly leveraged. By contrast, endogenous robots mostly operate independently of a human artist, in a stand-alone fashion, and creativity is drawn from some other source such as random numbers and events.

A typical example of an exogenous system could be a photocopier, printer, or plotter, which require and are directly controlled by a person's input. More uncommonly, prototypes can be controlled via facial images, eye movements, body movements, or sound: For example, a person can get their portrait done by showing their face to a humanoid robot (Calinon et al., 2005) or arm robot like "Obsessive Drafter," which draws on a large wall (Obsessive Drafter, 2021). Eye movements can be used to control a painting robot built by Faisal and colleagues (e.g., blinking to change colors) (Smith and Sayers, 2015). A person can dance to get Tate Corso's "Manibus" to summarize their motions as a painting (Crowder, 2017). Also, a person can play music to get WUSTL's Action Jackson to paint like Pollock (Action Jackson, 2007).

In contrast, an extreme example of an endogenous system that does not react to people could be a robot arm that is programmed to paint one specific scene, and nothing else. More complex systems can use aleatoric uncertainty to generate interesting art (Creative Machine, 2014): For example, Brown's "Computer Assisted Drawing" used random numbers with plotters in the mid-1970s, toward realizing autopoietic "art that makes itself" (Brown, 2003). Tinguely's Meta-Matics machines scrabbled with a pen over paper (Metamatics, 2014). Graffitizer used the randomness of ink drips on a wall to introduce complexity in its art, stemming from minute vibrations and variance in the amount of ink on a brush (Graffitizer, 2013). Additionally, Moon's drawing robot traced random map images from Google Maps, as well as the trajectory of a cricket's motions in a box (Moon, 2013). What was unclear from the literature was how these strategies compare and which would be desirable within the current context, in which a physically collocated robot and human co-create art.

1.1.2 Personalization

The idiosyncratic nature in which art is perceived also suggests the importance of personalization. Some related knowledge has been elucidated in the field of empirical aesthetics in regard to beauty evaluations ("beauty evaluation" refers to judging the degree of attractiveness of an artwork (Mallon et al., 2014)). For example, studies have reported on how general and personal taste influence human perception depending on the degree to which symbols are abstracted (Leder et al., 2016). But, how a robot can generate art which appears to express certain emotions such as happiness or sadness to an individual is less clear. For example, Van Gogh's Starry Night might seem dreamy or despairing; Bosch's triptych fascinating or frightening; and Dali's depiction of melting memory resigned or regretful, in the vein of Shelley's Ozymandias. Correctly identifying the meaning of a person's art could improve rapport, whereas mistakes could damage the trust a person has in a robot, especially in a therapy setting. More generally, personalization offers improved services which are easier to use, more satisfying, and more persuasive; such effects have also been seen in practice, for example, in positive emotions resulting from personalization of a robot in a language class (Gordon et al., 2016).

Personalization is conducted by applying knowledge of users to a system's behavior, and can be seen inter alia on the web in recommendations, advertisements, search results, and social media content; in interactive learning systems, through question selection based on "knowledge tracing"; in product development in the form of data-driven "personas"; and in commercial products such as mugs, shirts, books, and statues that use photos, names, or 3D data. Typically, personalization in the digital realm involves user models and profiles: a model describes how a user can be represented in terms of some properties of interest like name or gender, which is used to structure a user profile, the data for a specific user or group. Data can be obtained explicitly in a "user-driven" manner by directly querying users, or implicitly in a "system-driven" manner, where either approach has benefits and demerits; explicit user-driven approaches can overwhelm users, who also might not know exactly what they want from the start, whereas system-driven approaches can incorporate restrictive hidden biases.

Some concerns in defining a user model include what properties to consider and how to structure them, as well as how the data will be obtained and used. Many possible properties could affect the perception of emotions in visual art, with commensurately many possible model configurations. A naïve or brute force method might seek to obtain data for every single concept that could be expressed through art from a person, which is not likely to be practical. At a higher level of abstraction, stereotypes can be used; for example, properties felt to be important for the emotional rating of art that were included in the OASIS affective image dataset include age, gender, geographic location, race, ideological self-placement, and socioeconomic background (highest level of education, and household income) (Kurdi et al., 2017). For communication on social media, Zhao et al. proposed considering also social context, a person's previous emotional state, and influence of location (e. g., a photo taken in an entertainment venue might be happy, whereas a photo taken at a funeral might be sad), as well as personality via the Big Five model (Zhao et al., 2016, Zhao et al., 2019). Similarly, Rudovic et al. proposed a model to encode how autistic children show emotions in their audiovisual and physiological behavior, at three levels–culture, gender, and individual (Rudovic et al., 2018)–although other configurations might exist: for example, could the first layer be gender rather than culture, and what happens when other variables like age are considered?

Thus, the literature did not clarify how to design a socially assistive painting robot, which uses a personalized model to visually convey emotions; it seems like few studies have investigated the degree of overlap in people's perceptions of emotions in art, or how this can be modeled (also in terms of different forms of art, like abstract or representational) and how this can be transparently integrated into a system that can move from theoretical concepts to a concrete painting.

2 METHODS AND MATERIALS

2.1 Painting Together With a Human

The current section summarizes some of our previous work, which involved first identifying a basic scenario informed by the related literature (Cooney and Menezes, 2018). For simplicity, the basic scenario selected for exploration was dyadic (one human and robot), visual (non-verbal), and conducted over a single session (e.g., 10 min), with free choice of what to paint. Requirements for a robot included the capability to move safety near people and make art (human-like reach and cameras), as well as a familiar interface which could support social interactions (such as a "skeuomorphic" humanoid form). (A skeuomorph is an artifact that retains some ornamental features from some original form from which it was derived; e.g., to make it easy for a user to infer how it can be used (Skeuomorph, 2020). The humanoid form in an interactive social robot is here referred to as "skeuomorphic" because, unlike the humans after which they are designed, such robots typically do not need to be human-shaped, but rather use this form to leverage people's familiarity in interacting with humans, as a way to enable communication. In other words, humans can guess that a robot can see and speak if it has eyes and a mouth, etc). Based on these requirements, a Baxter robot was chosen. The human and Baxter robot can paint side-by-side, or face-to-face if the canvas is not vertical, but lying on a desk or table; for our study, the latter formation was preferable due to the robot's width–which can range from approximately 0.8–2.6 m depending on whether arms are tucked in or fully extended to its sides–and improved reach and visibility.

Based on this scenario, our group of artists and engineers followed a mid-fidelity research prototyping approach to gain some insight (Cooney and Berck, 2019). Thus, the artists guided the exploration of various different scenarios and setups, both interactively exogenous and endogenous, while the engineering students controlled the robot. Both artists contributed with their knowledge of art, in advising how the robot could seek to paint, which included materials and strategies, providing examples of sketches and paintings intended to express various emotions, and participating in various meetings, art-making sessions, demo events, and data collection (e.g., for a Brain-Machine Interface). Some additional information can be seen in **Appendix A**.

One idea that emerged from the sessions was that an exogenous robot could paint in a contingent way to indicate empathy. Contingent in Human-Robot Interaction (HRI) means "related" or "connected," such that there appears to be "a correspondence of one's behaviour to another's behaviour" (Pitsch et al., 2009). The simplest way to suggest that a robot can relate its art to what a human has painted is direct mimicking, or painting the same thing the human has painted. This felt interesting, in that the robot seemed to be perceptive and to attribute importance to the human's art. But, merely copying also felt like the robot was a mere machine, not a partner.

Another enjoyable interaction involved an artist painting together with the robot on a shared canvas, where the robot painted endogenously, independently of the artist. This felt creative and artistically interesting, since the artist could improvise, draw ideas, and build on what the robot painted. However, the lack of awareness from the robot of the human's behavior, and thereby the lack of a connection or bond, also felt like a human working with a machine, not a partner. Thus, both strategies felt limiting due to their one-way nature.

This led us to consider if a robot could produce art that balances exogenous and endogenous components to appear both empathetic and creative; thus, a robot could base its art partially on what a human does, and partially on its own intentions (e.g., to help the human to feel good). In general, such a need exists, for robots to interact effectively in relation to social and emotional aspects, to improve their competence and support positive user experiences (Lowe, 2019). For example, trust is desirable for a robot to be effective. Similarly, an ability to both consider other's behavior and produce something new could be useful in indicating some degree of intelligence–as robots that are perceived as intentional agents with a mind (i.e., "mind perception") are more likely to be treated as a partner and be the recipients of empathy, morality or prosocial behaviors (Wiese et al., 2017). Furthermore, creatively reshaping a human's emotional expression could lead to more stimulating, thought-provoking, and meaningful art–like in the "responsive art" approach, in which an art therapist provides visual feedback based on a person's art, toward exploring its meaning and achieving positive experiences. Also, the usefulness of appearing to balance exogenous and endogenous components in a robot's behavior to indicate agency has been previously suggested in HRI, within a related context of how a robot can direct attention toward interacting people (Kroos and Herath, 2012).

As a first step to explore such a strategy, the use of a "visual metaphor" was proposed: namely, that a robot can paint something that is similar in emotional meaning but different in creative expression. This is loosely in line with the concept of the "adjacent possible" (Tria et al., 2018) that describes first-order combinations of existing ideas, and based on our idea that different symbols can be painted to express the same emotion. For example, if a person paints a quiet forest, the robot could paint something else relaxing, like a babbling brook. Grieving people could be painted beside a remorseful grave scene. A snake poised to strike could be painted beside a threatening gun. Alternatively, bright balloons could be painted beside a festive stack of presents. This idea is general and can also be applied to abstract art. For example, if a person uses diagonal lines to express arousal, a robot could instead use a warm color to achieve a similar effect. Thus, the term "metaphor" here is used to describe such a different symbol that is intended to express a similar emotional meaning. For example, a painted circle could be seen as an abstract representation of a balloon, but might be useful to paint, not because there is any specific meaning in depicting a balloon, but rather as a metaphor to express an emotion of joy which leverages generally shared perceptions of the meanings of symbols.

This concept thus has both an emotional and a creative side, and art in general can be seen as comprising both sides, as discussed in "Expression Theory" (Khatchadourian, 1965). From the emotional perspective, our artists noted that art is created for various reasons; at any given time, an artist might be interested in expressing their own emotions, or in eliciting particular responses from an observer. For the context of a robot engaging in therapy or entertainment, the latter is the focus.

How then to incorporate this concept into a semi-autonomous interaction? As shown in **Figure 2**, a robot can detect when and where to paint; infer the emotional meaning of a person's art by analyzing colors, lines, and composition; select a contingent metaphor with an affective image database; generate an image based on the metaphor; and paint the image:

- (a) Canvas sharing. To avoid interrupting a person while they paint, a robot can either predict a person's intentions and motions and plan accordingly, or more simply, follow a turn-based interaction design. In the latter case, a person could indicate that it is the robot's turn to paint haptically, verbally, or visually–each with some potential demerits. For example, it might be difficult for a person with a cognitive disorder to haptically control a robot, which is not required in typical interactions with humans. Controlling a robot verbally using CMU PocketSphinx (Pocketsphinx, 2021) or Google Speech (Google Speech, 2021) might require ability to enunciate clearly at adequate volume; in our exploration we also noted that a non-trivial strategy would be required for the robot to deal with its own sounds, from speech to noise from actuators, as well as environmental noise. Moreover, visual control, via foreground detection through OpenCV (OpenCV, 2021)–either static or adaptive–could be used to detect a person's hands or brush moving over the canvas; but, during our simplified exploration, challenges were observed with illumination (flickering, shadows, and occlusions) and slight movements of the robot's arm with the camera, which generated false positives. Another alternative could be to combine various modalities for robustness. For this simplified initial exploration, a turn-based design with haptic control was implemented, in which a person presses a button on the robot's arm to indicate when it is the robot's turn to paint.
- (b) Art and Biosignal Analysis. To seem contingent, the robot should perceive what the human has expressed. Given that paintings are primarily visual, a camera, either on the robot or in the room, can be used to analyze a person's painting. Algorithms will likely become increasingly capable of high-level summarization and observation; currently, low-level and mid-level analysis is typical, which involves detecting colors, lines/shapes, composition, and depicted objects. One complementary alternative is to also detect biosignals linked to emotion, such as heart or

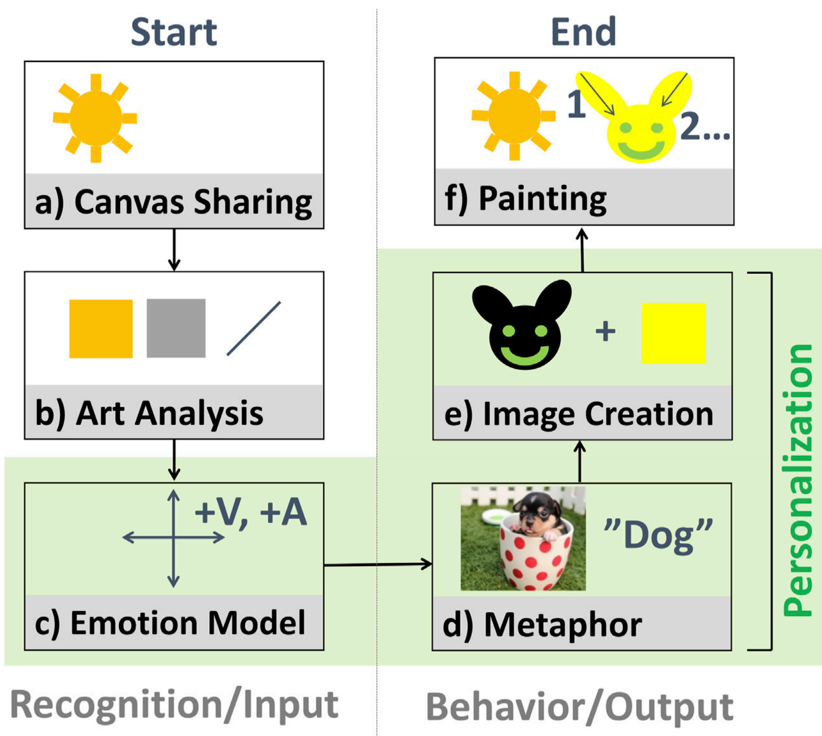

FIGURE 2 | A process flow for using visual metaphors to convey emotional contingency (empathy) and creativity in art that a robot creates with a human.

respiratory rate, skin conductance, muscle current or brain activity; we used the latter in our previous work, which required the user to wear a Brain-Machine Interface. For our current prototype, a camera on the robot was used. Conversion in OpenCV to HSV (Hue-Saturation-Value) space was conducted to color-pick six basic hues and calculate their average intensity, while using the Hough Transform to detect lines.

- (c) Emotion Inference. Next, the robot should seek to infer the emotional meaning underlying the physiological signals detected, such as visual expression or brainwaves. A generic model based on some emotion model could be used, or a personalized profile with information on how a person associates art with emotions, if available. How such a profile could be constructed based on querying a user is considered in the next section.

For our initial prototype, some simplified heuristics related to the visual arts were used in conjunction with a generic dimensional model of emotion: A linear combination of features based on detected colors and lines was used to calculate valence and arousal, for which Ståhl's model was used to calculate a contribution of each hue by area: this model provides a way to link colors to emotions, by rearranging Itten's color circle to fit Russell's Circumplex Model of Affect (Ståhl et al., 2005). Intensity also influenced valence, with light being positive and dark being negative, and the incidence of diagonal lines affected arousal.

- (d) Metaphor Selection. The next step involved finding a new way to express a detected emotional meaning. Nouns with a similar emotion connotation could be looked up via a large sentiment lexicon such as Affective Norms for English Words (ANEW) (Bradley and Lang, 1999), SentiWordNet (Baccianella et al., 2010), or WordNet-Affect (Strapparava and Valitutti, 2004), possibly with a concreteness rating to ensure that the noun can be expressed visually in a recognizable way; or, more simply, an affective image database could be used. A challenge identified was polysemy, which also related to bias and variance in data: for example, not all images of dogs will induce the same emotional responses, given disparities in canine size and aggressiveness, as well as human preferences and beliefs. A personalized profile could also be used here.

For our prototype, a simplified capability was implemented to search two affective image databases, namely the Open Affective Standardized Image Set (OASIS (Kurdi et al., 2017), which has 900 open-access color photographs assigned with normative emotion ratings, and the International Affective Picture System (IAPS) (Lang et al., 2008), which has 1,195 rated color photographs. For example, looking for happy, relaxed, sad, and angry emotions resulted in images showing dogs, flowers, gray yarn, and injuries in OASIS, and skydiving, nature, a cemetery, and mutilation in IAPS, respectively.

- (e) Image Generation (Reification). A plan is required to move from a metaphor like "dog" to a specific image of a dog to paint. For example, a generative approach, in conjunction with examples of dog images from Google Image Search or ImageNet (Deng et al., 2009), could be used to generate a "unique" image of a dog. This image could then be abstracted, and the color and lines modified to more clearly convey an emotion, or to less resemble previous images that the robot has drawn. A personalized profile could also be used for this step.

For initial exploration, Deep Convolutional Generative Adversarial Networks (DC-GANs) were used to develop compositions. Some challenges related to time were encountered, that prohibited the kind of online interaction we wished to achieve: web-scraping many images required much time; even with small MNIST-sized (LeCun et al., 1998) grayscale images, the algorithm took hours to generate new images; and the algorithm did not function automatically (a human was needed to select appropriate images from the output). Two simpler alternatives include applying filters to some automatically-combined web-scraped images, or asking artists to come up with images for some typical metaphors and manipulating these to create new images by reflecting, rotating, swapping colors, etc.

- (f) Painting Plan and Execution. Next, the robot should move to paint the target image on the canvas. This part of the process, although also challenging, has seen much focus in previous work, e.g., using visual control loops (Lindemeier et al., 2015) (It is also possible to simplify complicated images before depicting them, like in the work of Wang and colleagues, who used a CycleGAN and genetic algorithm for image-to-image translation (Wang et al., 2019).) An advanced algorithm might seek to also factor time into account and only conduct a subset of the most important strokes before giving the human another turn to avoid long waiting times. For our prototype, our artists and students were asked to generate some motions for the robot to perform based on created images. (Additionally, it was explored how the prototype could also seek to show emotions through a face in its display, as well as motion curvature and velocity, and voice, during painting.)

Above, steps (C)-(E) allow for personalization. As a useful starting point for exploration, the current article proposes a Folksonomic-style model, in which open questions are used to capture symbols that exert a large emotional effect on an individual. A Folksonomy is a taxonomy formed by allowing users to add their own idiosyncratic tags to describe content (McLean et al., 2007); such a sparse and flat model can be useful in complex situations like the current one where it might be unclear how to construct a complete taxonomy, or what kind of architecture would be appropriate. Moreover, given the high variance in how people could choose to emotionally interpret "tricky" concepts, and the estimated difficulty in accurately estimating what someone is thinking without direct input, an approach based on user-driven self-disclosure was adopted. To avoid overwhelming users, the number of questions was restricted and, for simplicity, single emotions were considered. Mapping from emotions to paintings via personalized symbols was explored by combining results from lookups in an affective image database, followed by post-processing. In doing so, the concept for the personalization module involved accepting a user identity and target emotional state as input, and outputting a paintable image expected to elicit this emotional state in the identified user.

This overall process for art-making can be repeated over multiple turns, thereby closing the "affective loop": perceiving emotions, acting, checking the result, and refining. A video describing this initial prototype is available online (Cooney, 2019).

2.2 User Study

In developing an initial prototype, the current article posited that people would rather interact with a robot that balances exogenous and endogenous content to appear both contingent and creative, rather than just one or the other, but arguments can also be made to the contrary: Since robot art systems today are often controlled by humans (exogenous) or paint independently without humans (endogenous), people might prefer a system that is not creative but is just controlled by them due to familiarity with using tools, as familiarity supports usability and technological acceptance, and control supports enjoyment; or conversely, people might prefer a system that is not contingent but generates good art regardless of human performance, and can surprise, kindle imagination, stimulate, and inspire. Moreover, questions existed about how people would perceive personalized art in various forms, such as abstract or representational.

To provide exploratory insight into these questions, a user study was conducted. As noted previously, the core approach in this article is speculative design, where often there is no user study (or even implementation); the user study here merely aimed to explore the above concepts from another perspective. For this, a simplified scenario was adopted in regard to robot strategies, the degree of personalization, the kind of art, and target emotions: For the robot's art strategy, three systems were considered:

- System 1: Exogenous (dependent on the person's art)
- System 2: Endogenous (independent of the person's art)
- System 3: Proposed (balancing both dependent and independent elements)

Personalization was examined in a binary manner, as either generic or personalized, where the generic art was taken into account as a starting point when developing the personalized art. Likewise, the form of art was examined in a binary manner, as either abstract or representational. Since the aim was to obtain insight into how visual expressions can be personalized and the focus was not on the implementation, paintings were represented using sketches which require less time to produce, following the spirit of our prototyping approach. For target emotions, four representative discrete emotions were selected, one per quadrant in valence-arousal space, in line with Russell's circumplex model (i.e., the corners of the "Affect Grid"): happy (high valence, high arousal), relaxed (high valence, low arousal), sad (low valence, low arousal), angry (low valence, high arousal) (Russell, 1980). (Three of these (happy, sad, angry) are also included in the six basic pan-cultural "Ekman" emotions, which do not include any relaxed emotion with high valence, low arousal (Ekman et al., 1969); a relaxed emotion was also represented for balance and due to its estimated importance in therapeutic applications.)

Various options exist for how to conduct a user study. As noted, the current article does not aim to verify or validate some complete solution in a formal lab experiment, which at the start would have been impractical and introduced many confounds (e.g., our prototype described in the previous section took several hours to generate images and was limited to dogs). Rather what was desired was a way to explore important concepts and gain initial insight to refine the design, like a survey. A survey offers a practical, safe way to acquire information that would be difficult to obtain by observation in order to form generalizations, especially given restrictions due to the COVID-19 pandemic; demerits include unsuitability when an understanding of historical context is required, bias due to non-respondents (less educated people are less likely to respond), intentional misreporting, and difficulty that respondents can experience in assessing their own perceptions (Glasow, 2005). Here these demerits were not prohibitive since historical context is not required, the intended sample population at our university is educated, intentional misreporting was not expected given that the topic is not controversial, and no better way appeared to exist to obtain feedback on respondents perceptions.

Thus, as a first step in our ongoing work, a simplified user study was conducted using an online survey: The main part of the survey checked our assumptions about a generic strategy and acquired data to build a personalized emotional profile; additionally, some extra insight was obtained into how participants perceived art generated using a Wizard of Oz approach based on their profile obtained in the first part of the survey.

2.2.1 Participants

21 adults at our university (6 female, 15 male; average age: 34.0, SD = 9.5, from 10 countries, where Swedish nationality was most common, followed by Iranian and Indian) participated in the first and main step of the survey. This included both faculty members and students in two computer science master programmes, such that all participants had at least an undergraduate degree in engineering or science. No members of our team, and no artists or art students, took part; and, participants received no compensation.

2.2.2 Ethics Statement

In Sweden, according to the ethics review act of 2003, additional formal approval by an ethics council is required for "interventions using methods intended to physically or mentally influence" participants, (SFS no 2003:460) (European Network of Research Ethics Committees, 2003). Since the goal of the survey was to observe and not to change participants' impressions in any way, and since sensitive personal information like race, politics, sexual behavior, or genetic/biometrics were not considered, the general principles described in the General Data Protection Regulation (GDPR, 2018) and Declaration of Helsinki (World Medical Association, 2018) were followed: The purpose of the study and basic approach were explained, and informed consent was obtained in writing, before beginning the survey. Gender, age, and nationality were temporarily collected to be able to report overall statistics that might influence perception of art; and in general precautions were taken to protect privacy and confidentiality, such as not storing names. Participation was completely voluntary and inclusive; the study design did not indicate the existence of an underrepresented group that should be targeted, but rather a range of different groups including students and faculty were invited to participate, and no vulnerable groups like minors under the age of 18 participated.

2.2.3 Procedure

Participants were sent links to a Google Forms survey (Cooney, 2020b), which took approximately 20 min to complete.

In the survey, participants answered questions about the robot's strategy for making art, then disclosed information about what symbols, representational or abstract, elicited emotions for them. First, for the robot's strategy, the participants were asked to inspect three images. For each image, the participants imagined that a human and robot has made art together, with the human's art depicted on the left side and the robot's art on the right side of the image. Each image represented an interaction with one of the three different versions of the robot–exogenous, endogenous, and proposed–as shown in **Figure 3**; for simplicity, the exogenous image was completely dependent on and similar to the person's art, the endogenous image was completely independent of and different from the person's art, and the proposed image contained a balance of both dependent and independent components. For each image, participants used a 5-point Likert scale to rate three statements:

- Q1 Contingency: "The robot's art fits emotionally with the human's art (i.e., the emotions expressed in both seem similar)."
- Q2 Creativity: "The robot's art is creative."
- Q3 Desire to use: "I would like to do art with this robot."

Thus, the technical term "contingent" was rephrased to be more easily understood by participants. In the second half of the survey, participants described which representational symbols and abstract colors and shapes made them feel happy, relaxed, sad, or angry. The participants were also given a chance to add free comments, which were then coded.

3 RESULTS

3.1 Art-Making Strategy

Figure 4 shows questionnaire results for how participants perceived the three art-making strategies.

The results were analyzed statistically. First, normality was assessed–which is a common assumption in some statistical

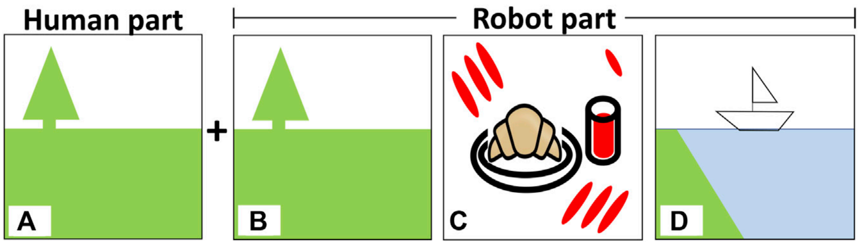

FIGURE 3 | Images used to assess how people feel about a robot's art-making strategy: **(A)** the human's part, **(B)** the exogenous system 1 (the robot's art is influenced entirely by what the human does), **(C)** the endogenous system 2 (the robot's art is not at all influenced by what the human does), and **(D)** the proposed system 3 (the robot's art seeks to express contingency and creativity by maintaining a balance of exogenous and endogenous concerns.

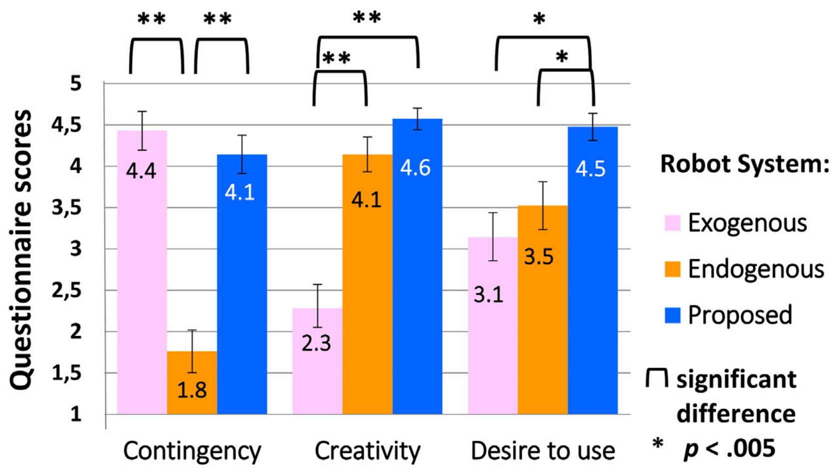

FIGURE 4 | Questionnaire results for robot art-making strategy.

tests–using Mardia's coefficients for skewness and kurtosis (Kurtosis, 2015). The assumption was violated for skewness in question 1, at $p < .001$, which was also confirmed by visually checking the histogram. Therefore, non-parametric tests were used: in particular, Friedman tests, which are appropriate for ordinal data from Likert scales (McCrum-Gardner, 2008). These tests merely indicate if significant differences exist; to find where the differences exist, Wilcoxon signed-rank tests are typically used along with an adjustment for multiple comparisons such as Bonferroni adjustments, which simply divide the overall significance level by the number of hypotheses. Additionally, Yates's chi-squared tests were applied to compare small amounts of categorical data, which are also common.

For question 1 about contingency, median ratings were 5, 1, and 4 for systems 1, 2, and 3, the exogenous, endogenous, and proposed systems; a Friedman test indicated that the systems were perceived differently in terms of contingency, $\chi^2(2) = 32.771, p < .001$. Post-hoc analysis with a Wilcoxon signed-rank test and Bonferroni adjustment indicated that the endogenous system 2 was perceived to be less contingent than either of the other systems (compared to system 1: $Z = -3.863, p < .001$; compared to system 3: $Z = -3.951, p < .001$). No significant difference was observed between the exogenous and proposed systems ($Z = -.907, p = .4$).

Likewise, the systems were perceived differently in terms of creativity for question 2, with respective median values of 2, 4, and 5; $\chi^2(2) = 26.800, p < .001$. A Wilcoxon signed-rank test with Bonferroni adjustment indicated that the proposed and endogenous systems were considered to be more creative than the exogenous system ($Z = -3.337, p = .001$; and $Z = -3.659, p < .001$). No difference was observed between the proposed and endogenous systems ($Z = -1.897, p = .06$), although with more data a trend might emerge, since there is variation in interpretations of what is creative (e.g., based on the degree to which usefulness is considered) (Diedrich et al., 2015).

Desire to make art with the robot also differed based on the robot's strategy, with median scores 3, 4, and 5 for question 3; $\chi^2(2) = 12.847, p = .002$. A Wilcoxon signed-rank test with Bonferroni adjustment indicated that participants would prefer to make art with the proposed version of the robot that appeared to be both contingent and creative, rather than just contingent or just creative (comparing system 3 and 1: $Z = -3.135, p = .002$; comparing system 3 and 2: $Z = -2.797, p = .005$). No difference was observed between the exogenous and endogenous systems 1 and 2 ($Z = -0.917, p = .4$). Furthermore, 14 out of the 21 participants said they would prefer to make art with the

TABLE 2 | Representational symbols disclosed by more than one participant as eliciting emotions. The top row indicates "typical" symbols described by more than one participant. Here the numbers beside each coded label indicate the number of mentioning participants, symbols that elicited more than one kind of emotion are indicated in bold, and comments in parentheses are given for clarification. The bottom row holds symbols indicated by only a sole participant.

Happy	Relaxed	Sad	Angry
Sports 9, family 8, food and drink 8, nature 8, traveling 5, sound (music) 4, work 3, visual leisure activities 3	Food and drink 10, visual leisure activities 8, sound (music) 8, nature 7, sports (exercise) 6, family 6, work (finishing work) 4, washing 3, rest 2	Failure 11, abusiveness 10, global problems (hunger, poverty, sickness) 8, family (missing) 7, injustice 5, nature (bad weather) 2, laziness 2	Abusiveness 9, injustice 9, ignorance 5, failure 3, sound (noise/shouting) 2, traffic 2
Freedom, gifts, bright colors, peace, truth, jokes, the smell of new books, happy endings, winning	Smiles, candles, silence, being in control	Bad news, seeing an "unhappy" plant, losing much money, witnessing others' sadness	Pretentious people, communists, blood, crowds, inaction of those who can act, irresponsibility, pain, losing something, when someone special does not obey, being late, some trump supporters

TABLE 3 | Abstract art elements disclosed by participants as eliciting emotions.

	Happy	Relaxed	Sad	Angry
Yellow	8	1	1	—
Orange	5	—	1	4
Pink	4	2	—	2
Purple	5	2	1	—
Green	7	8	—	1
White	6	8	2	2
Blue	8	7	1	—
Black	2	1	9	5
Red	2	—	3	10
Brown	—	—	8	—
Gray	1	1	1	1
Warm colors	1	1	—	1
Dark colors	—	1	1	1
(Subtotal)	48	31	27	26
Circle	8	8	3	1
Triangle	3	1	3	8
Square	2	2	5	2
Horizontal lines	2	9	1	1
Vertical lines	3	4	4	2
Diagonal lines	7	1	5	3
Curved	—	—	—	1
Everything	1	—	—	—
(Subtotal)	26	25	21	18
Total	74	56	48	44

proposed system, compared to one with system 1, and five with system 2 (one person said they would prefer either system 2 or 3); a Chi Squared test with Yates correction indicated a significant difference in this stated preference, $\chi^2(2, N = 20) = 11.213, p = .004$. The one participant who preferred the dependent system stated that the reason was because it was "doing work as like as human" (sic). The participants who chose the independent system stated that it seemed "interesting," "totally different," and "unconventional," arousing their intellectual curiosity (e.g., one participant wondered what pattern might underly its response and how reactive it was to a human's behavior).

Thus, the basic premise of this work was supported: that a contingent and creative system combining exogenous and endogenous components might be more desirable as an art-making partner than a system which is only exogenous and contingent, or only endogenous and creative.

3.2 Emotional Triggers

Participants' self-disclosures about which symbols elicit emotions are collected in **Table 2** and **Table 3**.

As expected, there was a high degree of variation in participants' responses: 433 labels were provided (207 representational and 226 abstract labels, or approximately half-half). The labels were grouped into 69 categories, whereof 21 were abstract (8 shape and 13 color), and 48 were representational. Only three abstract categories were mentioned by only one person each, compared to 28 representational labels mentioned only by one person each, such that 20 representational categories contained the vast bulk of these labels, or 179 labels. Thus, on average each participant provided 20.6 labels, whereof 9.9 were representational and 10.8 were abstract (for forms and colors), constituting a response rate of 2.5 representational and 1.3 abstract labels per question. (Note, this count indicates the number of unique participants who mentioned a category as eliciting an emotion in a specific question; participants sometimes used synonyms, so one participant writing that "injust and unfair" circumstances elicit sadness would be counted just once toward the category "injustice" for this question.)

For representational symbols, the most frequent symbols were sports, family, food and drink, nature for eliciting happiness; food and drink, visual leisure activities, and music for relaxation; failure and abusiveness for sadness; and abusiveness and injustice for anger. Thus, there was overlap: 10 of 20 symbol categories were reported by more than one participant for only one of the emotion categories, whereas the other 10 were reported for more than one emotion. Such overlap usually occurred between positive or negative emotions, rather than between aroused or relaxed emotions: For example, food and drink could be both happy and relaxing. Nature and family were considered to cause either happy, relaxed, or sad emotions; poor weather and missing family was associated with sadness. Failures in some cases could be related to work (e.g., references to "programming errors"), but in general there were not enough details to link these two categories.

For abstract symbols, out of 13 color categories, twelve (92%) were mentioned as eliciting both positive and negative emotions, and all 13 were considered to be both calm and aroused. The only exception was brown, which was only negative and calm (sad).

White, black, and gray were explicitly described as eliciting every emotion, although if only colors mentioned by at least two participants are considered, this drops to only white. Also, some participants mentioned "warm colors" instead of specifying individual colors, but if this is taken into account, then red, yellow, and orange also encoded for all four emotions. Nine categories were furthermore described as eliciting three out of four emotions.

The amount of overlap within individual participants' responses was also checked. Ten (48%) of the participants' responded in an overlapping way, in that one color could encode for more than one emotion (e.g., black for both sadness and anger), whereas the remaining eleven participants (52%) mentioned distinct colors for each emotion. In one extreme example, one participant wrote the same answer for all emotions: "graphite gray, black, white."

15 participants (71%) indicated more than one color for one or more emotions, whereof two participants listed more than one color for each emotion, and one participant listed eight colors that felt happy. In contrast, six participants listed at most a single color that made them feel each emotion, with two participants mentioning a total of three cases in which no colors could express an emotion.

For shapes, there was likewise much variation and overlap. All categories mentioned by more than one participant (excluding "curved" and "everything") were felt to elicit every emotion. Happiness was mostly shown by circles and diagonal lines, relaxation by horizontal lines and circles, sadness by squares and diagonal lines, and anger by triangles and diagonal lines. From the perspective of how each shape was perceived, circles seemed to be happy and relaxed, triangles to be angry, horizontal lines to be relaxed, diagonal lines were everything except relaxed (strongly showing various emotions), and vertical lines and squares seemed to be fairly uniformly spread out among the four categories.

Seven participants (33%) reported that a shape category expressed more than one emotion. (Two had overlap in saying that no shapes expressed certain kinds of emotions for them, like no shapes were negative.) Also, another seven participants (33%) mentioned two or more shapes for at least one emotion. Furthermore, four participants mentioned a total of eight cases in which no shapes could express an emotion.

Along the way, it was also observed that there were more responses for positive than negative emotions, with some participants mentioning that all shapes seemed positive, possibly due to their engineering background, or giving no responses at all regarding negative emotions. Additionally, various references were made to personal information that was not provided through the survey: e.g., "my cat," "my programming errors," "my home," "my brother," "my child," "my mom," and "my parents." Without knowing more, it is difficult to depict such symbols visually: for example, should "my cat" be depicted as a giant Norwegian Forest cat, or as a tiny Munchkin?

3.3 Extra Insight: Assessment of the Sketches

The user study provided some general insight into how interactive art-making might be perceived, but left a question: Could personalized art based on self-disclosure more clearly convey emotions than using a general model? A concomitant challenge was that it was not clear if users would be able to accurately report which kinds of visually depicted concepts will best express various emotions to them. To gain some additional insight, four participants who completed the survey were asked to complete a follow-up survey (3 female, 1 male; average age: 30.2, SD = 5.0). These participants were again sent links to a Google Forms survey, which was this time personalized. In total, the follow-up survey took approximately 10 min to complete.

To prepare the follow-up survey, the participants' responses in the first survey were used to generate art in the form of eight personalized images (four abstract and four representational, thus two images per emotion). Personalized sketches were generated offline using the Wizard of Oz technique. The participants' responses were input into Google Image Search for images labelled free to reuse. To minimize the risk of using specific images that might communicate unintended signals, "clip art" was added to the search. For search queries where no appropriate image was found, synonyms were used. Images were manually selected to download and assembled into a single composition, before an art program effect was used as the last step to make the composition appear like a painting (Paint.NET) (Paint.NET, 2021).

The eight generic images were created once and used for all participants. Representational images were generated based on OASIS (Kurdi et al., 2017). The most extreme four OASIS images were identified corresponding to each emotion target. Abstract images were generated by our artists in line with our previous work based on heuristics including Ståhl's model (Ståhl et al., 2005). Again, art program effects were used to ensure that the sketches looked like paintings.

After generating the sketches, the participants were invited to complete the follow-up survey. This involved assessing 16 images (personalization (yes or no) vs. art type (abstract or representational) vs. four emotions). First, participants were asked to describe their current emotional state and if they had knowledge about art, to identify potential outliers; i.e., participants who were in an uncommon emotional state or who indicated high artistic knowledge that could involve strong preconceptions. Then the participants conducted four comparisons, once per emotion, in which they ranked the four images for each emotion (personalized/representational, personalized/abstract, generic/representational, generic/abstract) in order of how much the images expressed each emotion (happy, relaxed, sad, angry). Additionally, as a check to see how the participants perceived individual sketches, the Self-Assessment Manikin (SAM) was used to rate the valence and arousal of each sketch before comparisons (Bradley and Lang, 1994); the SAM is a tool for categorizing emotional responses to stimuli, which uses some cartoon pictures of a human smiling or frowning, and the presence or lack of some wiggly lines, to illustrate a range of valence and arousal, with the aim to be easily understood by laypersons. Image orders were randomized, and each participant received a personalized form for the follow-up survey. **Figure 5** shows the eight generic sketches used, and **Figure 6** shows 32 personalized sketches also generated based on the self-disclosed data from participants.

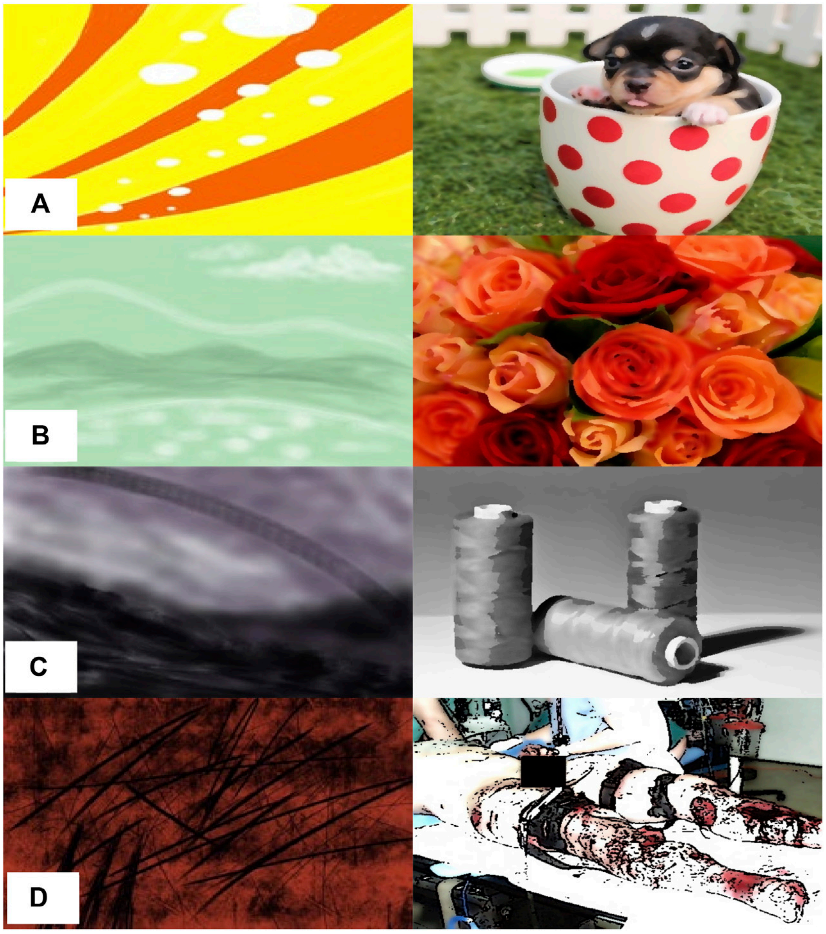

FIGURE 5 | Generic sketches: (left) abstract, (right) representational; **(A–B)** happy, **(C–D)** relaxed, **(E–F)** sad, **(G–H)** angry.

The first step in analysis was to identify potential outliers based on the preliminary questions about emotional state and artistic knowledge. One outlier was detected: in contrast to three participants who felt well, the remaining participant stated that they felt “depressed.” Furthermore, although none of the participants indicated strong agreement that they have artistic knowledge, the depressed participant’s self-rating was the highest in the group (6, compared to the average of 4.2, SD = 2.2). Examination of the data from the depressed participant indicated some anomalous responses that appeared to be different from those of the other participants and general expectations from the OASIS dataset analysis, and possibly inconsistent and random: For example, the sketch of a small puppy selected by the participant as the happiest of the four images in the comparisons was rated as highly negative via SAM. The generic sketches of an injured bleeding person, as well as the sad and angry generic abstract sketches, were assessed with the most positive score possible. Additionally, a pattern could not be seen in the comparisons, with a different category considered to best express emotion each time. Thus, although there might have been some effect related to artistic preferences, or some external factor such as time pressure, the inconsistencies might have been unintentional due to feeling depressed, which can involve anhedonia and negative fixation (in this case, possibly a loss of joy in seeing positive images, loss of interest in filling out the survey, and interpretation of typically negative symbols such as death by injury as positive).

Based on this, the data were analyzed in two steps, both with and without the outlier data (4 vs. 3 participants). Using all of the data, the personalized representational art was most frequently described as best conveying the intended emotions (75%, 12/16); and, a Chi-squared test with Yates correction confirmed that the participants seemed to perceive the systems differently ($\chi^2(3, N = 16) = 17.8, p = 0.0005$), although caution is advised in interpreting this result due to the small number of participants. By contrast, the generic representational art was most frequently described as least conveying the intended emotions (44%, 7/16), and abstract art, generic and personalized, was rated as being in the middle. Also, the most extreme valence and arousal ratings were associated with the personalized sketches. With the consistent data from the 3 non-depressed participants, there was only one case in which the personalized representational art was not indicated as best conveyed the intended emotions (vs. 92%, 11/12), which might have occurred due to ambiguity: this

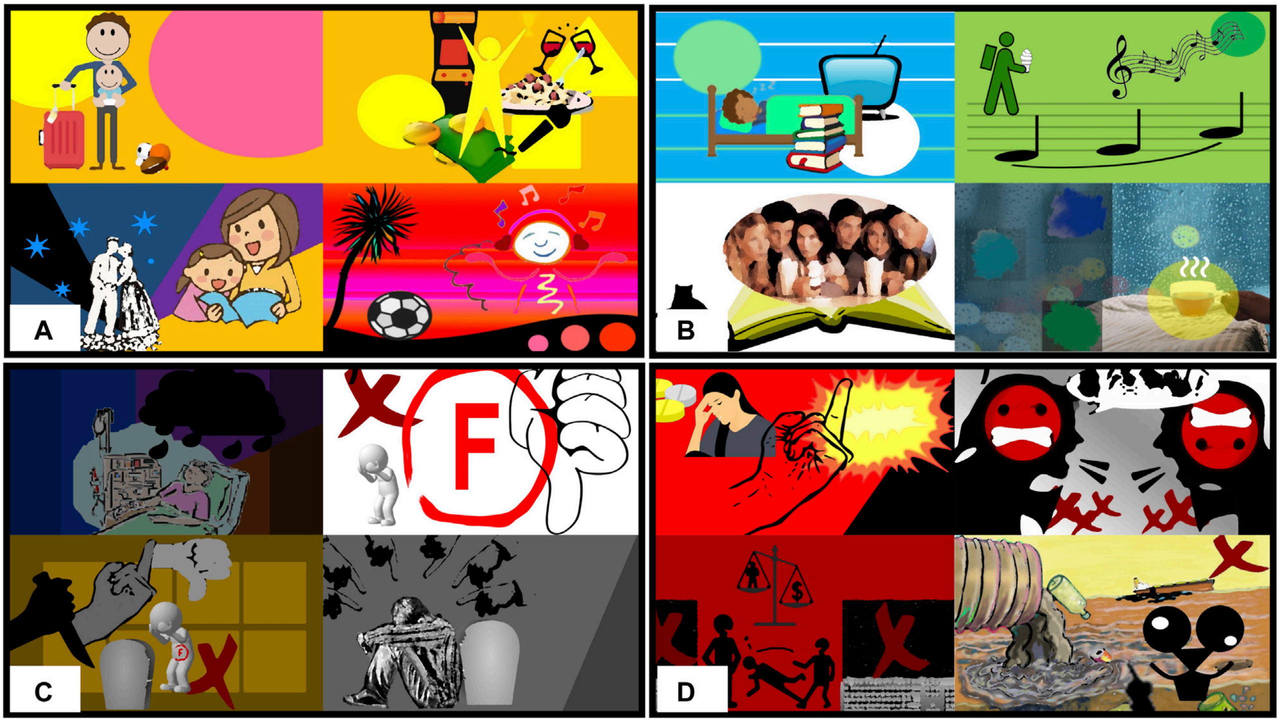

FIGURE 6 | Personalized sketches for four participants: **(A)** happy, **(B)** relaxed, **(C)** sad, **(D)** angry.

participant disclosed that warm colors seemed both happy and angry, and had indicated abstract symbols such as “ignorance” that might have been difficult to accurately express visually in a sketch. As with all of the data, the most extreme valence and arousal ratings were also associated with the personalized sketches: the most positive valence and arousal scores were given for the personalized representational sketches expressing happiness (1.3 and 2.3 on the 9-point scale), lowest valence for the personalized representational sketch expressing sadness (8.7), and lowest arousal for the personalized abstract sketch expressing relaxation (7.5). Along the way, the variance in scores for representational and abstract art was also checked; for valence, there was more average variance for abstract art than representational art (1.5 vs 0.85), but the case was reversed for arousal (1.5 vs. 2.2).

3.4 Bringing Things Together

As noted, the aim of the current article was to start to explore this complex landscape and stimulate discussion, rather than to develop a fully functioning prototype, but nonetheless, a rough proof-of-concept was additionally built to draw together and exemplify some of the insights and concepts developed in the current article: This robot prototype uses general norms, in the form of the visual metaphor concept, to appear contingent and creative, and focuses on symbols that were identified as typical (related to nature, which was part of the online survey, and also rated as one of the most common symbols that can be happy or sad). Furthermore, the robot uses a person’s self-disclosure with representational symbols to personalize its art, which seemed to be easier to use and clearer than abstract symbols for the current context.

Specifically, before the interaction, a person answers some questions about which symbols elicit their emotions. Then the robot starts the interaction with a quick introduction, asks the person to draw a grass field, and records an image of the person’s painting. This analysis results in a judgement if the person’s painting is happy or sad, based on features such as intensity, color, and shapes, as described previously. Then, the robot seeks to express contingency and creativity by painting a different natural scene (e.g., either mountains or sea, depending on the person’s emotional art profile) with a similar emotional feel. Although highly simplified, this interaction brings together some of the concepts discussed in the current article on emotional contingency, creativity, general norms, and personalization, which is also illustrated in a short video demonstration (Cooney, 2020a).

4 DISCUSSION

In summary, the current speculative article used a collaborative prototyping approach, including a small user study, to propose a design for a robot to paint with a person in a contingent, creative, and desirable manner, based on personalized visual metaphors. General strategies and personalization are discussed below, followed by identifying some limitations and challenges for future work.

General Strategies

Some patterns could be identified overall and for representational and abstract art:

- Overall: A central finding in this article was that participants preferred to make art with a balanced system that is both contingent and creative.
- Representational: Also, a small number of 20 frequent categories was identified for representational symbols; the categories most associated with emotions seemed reasonable, because positive effects of physical activity, affection, diet, music, nature, and hobbies are well-known, as well as negative effects of failure, abuse, and injustice. (Appraisal theory also indicates the role of perceived agency in shaping sad vs. angry emotions: abuse can be either impossible or possible to prevent, thereby causing either sadness or anger, whereas reported failures and injustice referred to the respondents themselves, and to others, respectively–here, actor-observer bias suggests that we tend to attribute our own actions more to circumstances outside of our control, and others actions more to potentially avoidable character flaws.)
- Abstract: Some general patterns were also identified for abstract symbols. For colors, the idea that white, black, and gray could express various emotions was not surprising, as black and white art, comprising various shades of gray, is common in media such as comic books, which have been used to express a full gamut of emotions. The association of brown with sadness, although unexpected, also made sense, as brown is a composite color comprising yellow and red with black, which can be thought of as dark orange, and darkness is associated with negative emotions like sadness. However, responses about the emotional meanings of colors did not always agree with Ståhl's color model; for example, colors in the negative quadrants like purple were considered also to be happy. This could indicate a cultural influence, or a more complex association of a range of various saturations, intensities, and hues with such labels–regardless, it also suggests that such generic guidelines should be taken with a grain of salt, and that personalization can be useful.

For shapes, the finding that circles seem to be positive and triangles to be negative is supported by previous experiments (Heider and Simmel, 1944). Likewise, the observation that horizontal lines can be seen as relaxed and diagonal lines as dynamic (not relaxed) has also been previously indicated (Rodin, 2015). Furthermore, it seems reasonable that diagonal lines would be reported frequently as eliciting emotions because high arousal symbols are more commonly reported than low arousal symbols when seeking to express high or low valence. Also, the lack of consensus regarding vertical lines and squares suggested that additional emotional categories might be required to gain insight into their emotional meanings.

Personalization

A Folksonomic-style model was used to gather 20.6 self-disclosed labels per person (433 labels for 21 people) for personalization, avoiding the need to know ahead of time what categories to use; participants' self-disclosed perceptions of emotions in art were observed to be highly idiosyncratic and varied greatly–in line with previous work.

- Overall: A central finding was that personalized representational symbols seemed easier to use and clearer than abstract symbols.
- Easier to use: Participants disclosed more information about representational than abstract symbols (2.5 labels, vs. 1.3 labels per question), possibly because fewer abstract categories exist. Furthermore, although all participants were able to describe representational symbols, some participants were not able to describe colors or shapes that expressed an emotion.
- Clearer: Representational symbols also seemed to be more monosemic, and have less overlap between positive and negative emotions than abstract symbols. It seems encouraging that 10 typical categories, and 28 one-label categories, were uniquely tied to one emotion, suggesting that such emotional communications will be perceived as intended. As well, there is some ambiguity associated with abstract symbols; for example, a circle could remind someone of either positive symbols like an angel's halo, candy, or a soft pillow, or negative symbols like a pit, an open garbage can, or a shark's mouth gaping wide to violently rip into its prey. Intuitively, this seems to be supported by how humans interact in everyday conversations: when someone asks how we are, we usually mention specific experiences, like doing well on an examination or feeling bad due to a cold; we don't usually talk about feeling good or bad due to a color or form. Additionally, the small follow-up survey appeared to indicate that for some participants, self-disclosure can be used to better communicate emotions through personalized representational art, rather than personalized abstract art or generalized representational art.

Limitations and Future Work

Next steps will include conducting more rigorous user studies, overcoming practical challenges, dealing better with some people who for whom personalization seems to be more difficult, improving personalization of abstract art, and exploring other applications:

- Explorative results. These results are limited by the speculative, exploratory approach. As noted, the current article was not intended to provide some final answer as to how robots can interact with people in an emotional and creative way; rather, the aim was to explore some early stage ideas for such a design and stimulate discussion that could aid the design of a variety of future systems, as in some previous articles that have followed a speculative design approach (DiSalvo et al., 2003; Luria et al., 2020). In the

TABLE 4 | Examples of effects of culture, age, gender on visual aesthetics.

	Representational	Color	Shape	References
Culture	Swastikas can be a positive symbol for buddhism in the east or a negative symbol of the horrors of war in the west	Red is associated with communism, which could be interpreted positively or negatively	Aesthetic preferences for simplified, imperfect lines in Japanese wabi-sabi have been contrasted with a western preference for perfect, controlled shapes	Holman and Vertegaal, (2008)
Age	Elderly can prefer skeuomorphic rather than flat designs; young children might not recognize obsolete symbols such as video rentals, card catalogs, hole-punched floppy disks, and rotary-dial telephones	Elderly typically prefer colors of shorter wavelengths (blue, green, and violet, vs. red, orange, and yellow)	Infants have a visual preference for curved shapes (especially faces similar to their carer, but also shapes like bull's eyes), and females of reproductive age prefer masculine (square) faces more than females in puberty and post-menopause	Fantz and Miranda. (1975); Holman and Vertegaal. (2008); Little et al. (2010); Birren. (2016)
Gender	Girls typically draw more realistic, docile scenes with nature and fewer objects	Girls typically use more colors than boys, including more blending and harmonious combinations	Girls typically use more curved and fewer rectilinear shapes	Tuman, (1999)

experiment conducted, a wide range of cultures and nationalities was represented, the sample range in age was large, and the numbers of female and male participants were unequal. However, it is known that culture, age, and gender and various other factors can affect visual preferences, as in the examples shown in **Table 4**. Now that some basic insight has been obtained, it would be beneficial to conduct user studies with larger, more uniform groups of participants, also not just from the field of engineering, to elucidate the effects of such factors. Moreover, an autonomous robot system can be used instead of a Wizard of Oz approach. This could be in a lab, or better still, in the "wild."

- Practical and technical challenges. Prototyping indicated that a current bottleneck is timely generation of novel images that does not require a human in the loop to identify appropriate images to paint; smaller problems include noise in real human environments related to lighting and motion, as well as a seeming lack of easily reusable code for painting robots to render images, possibly due to the high diversity of robot morphologies.
- Abstract art. Another challenge is that it seemed more difficult to personalize abstract art than representational art. Three potential causes suggested themselves: 1) Personalized preferences for abstract art often overlapped with general guidelines–e.g., red and black colors with diagonal lines to represent anger–whereas, the space for representational art is much more expansive; for example, no participant described the contents of the generic image, a small puppy in a cup in a grass field, when queried for a happy symbol. 2) Another potential cause is that the participants might not have known ahead of time what kind of abstract art would make them feel a certain way, which was indicated in some comments. 3) Finally, our measurements in the sparse, open-ended survey might not have been sufficient to model participants' preferences. For 2), a reflective approach to personalization, intended to empower users by querying to encourage thought about goals before starting an activity, might be useful (Lee et al., 2015). (Another interesting observation in the same work was that, although robot designers typically try to avoid boring people with repetition, human experts suggested the importance of repeatedly querying users to uncover hidden motivations.) Additionally, Big Five analysis (John et al., 2008) could be used to stereotypically infer a person's perception of art: e.g., if positive emotions could be experienced by linking conscientiousness to clean lines and shapes, openness to more novel art, or extraversion to stronger colors and color contrasts. For 3), aside from introducing more questions and considering other factors such as composition, interactive personalization could be used throughout a more extended period (Clabaugh, 2017), possibly like the series of questions in an eye exam; similar to the above work by Lee et al., despite foreseeing a possibility of survey fatigue, participants in this work also reported enjoying being prompted frequently.
- Difficult individuals. Some participants seem to be easier to make art for than others; specifically, participants who listed more representational symbols, colors, and shapes that elicit emotions, while not using the same symbols for multiple emotions, and providing sufficient information to be able to visually depict images: Typically, paintings use more than one color or shape, so it might be easier to prepare art for participants who listed more options. Likewise, it might be easier to express emotions in artwork for participants who did not say that one color or shape expressed multiple emotional meanings to them. Additionally, some participants referred to personal information, like "my family," which alone could be insufficient for visual depictions. Another challenge was noted with the seemingly inconsistent appraisals by the depressed participant; in a therapeutic context, robots will probably frequently interact with people with depression; therefore, such persons should not be excluded or marginalized, but rather centralized in at least some human models.

To acquire better data, motivation can be clarified for those participants who responded with only few or overlapping labels: Was there an underlying difference in how they perceive emotions in art or some other confounding reason (e.g., was there an assumption that responses had to be non-overlapping (demand characteristics), or were some tired of the survey and trying to get it done fast)? Survey instructions could then be refined, gaps could be caught at the time of profile creation, or a robot system could query afterwards for more information, although in any case there is a need to be careful about ethics in treating personal information. To determine if a painting will be able to correctly convey an intended emotion to someone who is depressed, one way to seek to avoid miscommunications might be to use a multimodal strategy to better detect and convey emotions: in addition to analyzing art, a robot can check a person's emotions via a Brain-Machine Interface, and verbally ask for confirmation that these emotions have been correctly identified, before describing its intentions as it paints.

- Other applications. The concepts here could be applicable to other kinds of art, from sculpture to photography, drawing, and other crafts. Moreover, the usefulness of ensuring a balance between exogeny and endogeny, and thereby emotional contingency and creativity, might not be restricted only to painting robots; rather a similar pattern might be useful for interacting with humans in various contexts, such as advertisement, writing, music, and games. For example, the author of the current article was part of a team that set up an android in a department store as a kind of lifelike, moving mannequin in a Valentine's Day display for two weeks in February 2012 (Geminoid F, at Takashimaya in Shinjuku, Tokyo) (Mar 2017); the android's code sought to balance reacting to people who came close and waved, with having her own agenda, like looking at her smartphone or absentmindedly to the side, with varying emotions. In writing haikus, there is often a "timely" exogenous component shaped by a poet's perception of a moment, as well as a "timeless" endogenous component, revealing the inner life of the object of the poem (Higginson and Harter, 1989). In music, improvisations can involve reactive exogenous skills, e.g., to stay aligned with a change of rhythm, and endogenous compositional skills, e.g., to flesh out a musical fragment (Alperson, 2010). In playing games with a human, positive effects have also been observed for robots that combine exogenously reacting in a large, meaningful manner, with exhibiting its own consistent endogenous intentions (Cooney and Sant'Anna, 2017). Future work will involve identifying other contexts where such a design could be useful.

Consideration of such topics could allow such robots to exert a positive influence on interacting humans.

5 CONCLUSION

This article suggested the "smart phone hypothesis," that social robots will become accepted into various human environments when they become capable of interacting in a variety of useful ways, including within challenging applications involving emotions and creativity, like art-making. A speculative approach involving collaborative prototyping with artists and engineers, along with a small user study, provided some insight into practical challenges such as timely autonomous image generation, as well as general strategies and personalization:

- General: participants would prefer to make art with a robot that is both emotionally contingent and creative, rather than merely one or the other, which can be done by balancing exogeny and endogeny; also, some shared patterns could be identified for both representational and abstract symbols, such as that personalizable symbols such as sports, food, family, and nature are perceived in a positive way
- Personalized: participants' self-disclosed perceptions of emotions in art were highly idiosyncratic and varied greatly, in line with observations in previous work, suggesting also that some participants' perceptions might be easier to model than others; also, representational symbols appeared to be easier to use for personalization than abstract symbols, in terms of encouraging more disclosure, being less ambiguous and more easily related to individual emotions, and seeming to more clearly convey emotions in some sketches.

These results were discussed with the aim of stimulating ideation, which included proposing some next steps in terms of reliability, practicality, challenging cases, art forms, and other applications.

The basic contribution is insight into some considerations for art robots that could help to support well-being in interacting people. At a higher level, exploration in this research direction could potentially facilitate technological acceptance for robots in human spaces, and also eventually provide an opportunity for us to learn about emotions and creativity, two phenomena which are tightly intertwined in our natures as humans.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because emotional perceptions could potentially be used to identify individuals. Partial data for which this is not a concern could be made available. Requests to access the datasets should be directed to martin.daniel.cooney@gmail.com.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

Ideation, experimentation, and writing were conducted by the sole author, MC, who is accountable for the content of the work.

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Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX A: OUR TEAM

Since starting in 2017, 63 people have been directly involved: two artists, two researchers, one PhD student, 26 master's students (two in particular), two undergraduate students, and 30 experiment participants. More people have been involved indirectly, comprising at least 30 observers to a free demo event; classes of students and researchers who discussed thesis results; and people who have read, listened to, or watched various newspaper articles, radio appearances, and thirteen YouTube videos showing this work with robot art, which have also been viewed over a thousand times as of October 2020.

The two artists on the team were Dan Koon and Peter Wahlbeck: Dan Koon is an American artist and author living in southern Sweden, who was self-trained from copying masters such as Rembrandt, Vermeer and Monet. He uses mainly acrylics and iPad sketches to seek to portray nonmaterialistic aspects of the individual, such as existence and creation. Peter Wahlbeck is a Swedish artist, comedian, and actor, who has been making art for over 30 years. He likes to make people happy and get them to laugh, which can be seen in the vibrant, colorful and creative characters that appear throughout his work. His paintings, although intended more to decorate than to convey political messages, yet seek to stimulate thought. Some of their art is shown in **Figure 7**.

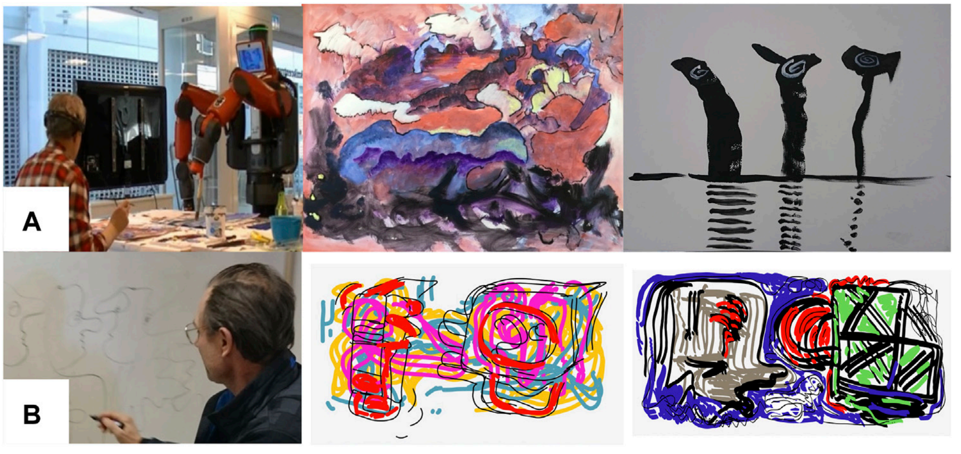

FIGURE 7 | Two professional artists assisted in our exploration by providing advice and creating examples of emotional art, e.g.: **(A)** some art by Dan Koon showing use of color and form, **(B)** some art by Peter Wahlbeck showing positive and negative emotions.