EXPLORING HUMAN-COMPUTER INTERACTIONS IN VIRTUAL PERFORMANCE AND LEARNING IN THE CONTEXT OF REHABILITATION

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EXPLORING HUMAN-COMPUTER INTERACTIONS IN VIRTUAL PERFORMANCE AND LEARNING IN THE CONTEXT OF REHABILITATION.

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EDITORIAL
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Editorial: Exploring Human-Computer Interactions in Virtual Performance and Learning in the Context of Rehabilitation

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Editorial on the Research Topic

Exploring Human-Computer Interactions in Virtual Performance and Learning in the Context of Rehabilitation

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Virtual reality (VR) environments are becoming increasingly prominent in rehabilitation (Howard, 2017), but much remains to be understood about the influence of human factors on the effectiveness of virtual interactions. VR environments relevant to rehabilitation contexts vary in terms of interaction interface requirements and methods of input and control (Lubetzky et al., 2020). Other technological affordances such as level of immersion, the type of feedback provided, or the complexity of audiovisual graphics may also influence outcomes in rehabilitation contexts, and the extent to which interactions in virtual environments transfers to improved outcomes in real life. In order to support the emerging evidence-base, it is important to understand how user characteristics interact with the technological attributes of virtual environments to influence performance, behaviors and learning. The goal of this Research Topic was to highlight insightful and multidisciplinary examples of the potential impact of human-computer interactions in virtual environments in the context of rehabilitation.

Many of the articles in this Research Topic discuss the need for human-computer interfaces to individualize interventions by tapping into the emotive aspects of rehabilitation. To this end, Elor and Kurniawan present a bridging review that links immersive virtual reality to rehabilitation. They propose a theoretical framework that informs design of a computationally-adept medium for physical rehabilitation. Their framework expands the perception of VR by proposing a rehabilitation-specific VR system which would integrate emotional feedback, among other outcomes collected in real-time.

Croucher et al. present the use of embedded context-sensitive attractors to guide attention and walking direction during virtual reality-based clinical walking interventions. The authors posit that verbal directions provided in virtual environments reduce participant autonomy and they argue that the investigation of such context-sensitive attractors is a step towards enhanced virtual rehabilitation. Willis et al. explored the spatial relationships between visual and tactile stimuli. In their investigation of visual capture of a tactile sensation, the authors promote the concept that perception is individual and matters to the design of virtual environments for rehabilitation, specifically for individuals with phantom limb pain.

Two other studies in this Research Topic present further findings to support the need for personalization in virtual reality environments. De Castro et al. explore commercially available accelerometers for home practice of motor tasks in persons post-stroke. The findings from this study highlight the need for machine learning algorithms to present clinically-relevant data and guide rehabilitation treatment planning. Brown and Powell present evidence to support the need for a pre-exposure baseline measure of cybersickness in people with chronic pain to support better interpretation of findings from research studies using head-mounted displays in rehabilitation. Each of these articles provide robust evidence for the need to personalize components of human-computer interactions in virtual environments, as well as to better the understanding of specific patient populations, to support optimal rehabilitation and learning.

The remaining articles in this Research Topic discuss transfer or generalization of performance in a virtual environment to the real world. Joyner et al. compared performance of a dexterous task in VR and real-world environments in order to improve VR-based training for individuals with technologically-advanced upper limb prostheses. The authors suggest that unrealistic physics and object occlusion are important characteristics of the virtual environment to consider when designing for success in the real world. Keshner and Lamontagne argue that characteristics of virtual environments must be executed and applied carefully to support transfer to real-world performance. Though their research is in balance and gait in neurological disorders, they highlight how virtual environments that enhance perception-action coupling lead to better real-world performance. Harvie discusses specific features of VR that can support active learning, improve access, and increase transfer of learning and skills to the real world for individuals with chronic diseases taking part in self-management interventions. Lastly, Furmanek et al. present research on how components of the virtual environment, specifically hand-object collisions, impact perception-action dynamics and reach-to-grasp coordination both in the virtual environment and in the real world. Together, these studies add to the literature on virtual environment design to advance our understanding of its importance on transfer of training.

Hoeg and colleagues present a systematic review and meta-analysis of virtual reality-based rehabilitation in older adults. The review and analyses classify studies based on level of immersion and present a taxonomy of virtual rehabilitation systems. The paper is a call to action to the field of virtual rehabilitation to address the ambiguity of definition of VR and immersion. All the papers in this Research Topic illuminate what is currently known about the influence of human factors in learning in virtual rehabilitation contexts, identify subsequent research directions, and inform decision-making about clinical use of VR environments in rehabilitation.

AUTHOR CONTRIBUTIONS

RP drafted and edited the article. SG, TK, BL, DL, AL, WP, and MR edited the article. All authors approved the final version for submission.

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REVIEW
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The Ultimate Display for Physical Rehabilitation: A Bridging Review on Immersive Virtual Reality

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Physical rehabilitation is often an intensive process that presents many challenges, including a lack of engagement, accessibility, and personalization. Immersive media systems enhanced with physical and emotional intelligence can address these challenges. This review paper links immersive virtual reality with the concepts of therapy, human behavior, and biofeedback to provide a high-level overview of health applications with a particular emphasis on physical rehabilitation. We examine each of these crucial areas by reviewing some of the most influential published case studies and theories while also considering their limitations. Lastly, we bridge our review by proposing a theoretical framework for future systems that utilizes various synergies between each of these fields.

Keywords: immersive virtual reality, virtual reality therapy, immersion, presence, emotion, perception, multimodal displays, biofeedback

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1. INTRODUCTION

In 1968, Ivan Sutherland, one of the godfathers of computer graphics, demonstrated the first head-mounted display (HMD) immersive media system to the world: an immersive Virtual Reality (iVR) headset that enabled users to interactively gaze into a three dimensional (3D) virtual environment (Sutherland, 1968; Frenkel, 1989; Steinicke, 2016). Three years before the "Sword of Damocles," Sutherland described his inspiration for the system in what became one of the most influential essays of immersive media: "*The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming, such a display could literally be the Wonderland into which Alice walked*" (Sutherland, 1965). Morbidness aside, this vision of an ultimate display asks if it is possible to create such a computationally adept medium that reality itself could be simulated with physical response. Sutherland's "Sword of Damocles" helped spark a new age of research aimed at answering this question for both academia and industry in the race to build the most immersive displays for interaction within the virtual world (Costello, 1997; Steinicke, 2016). However, this trend was short-lived due to hardware constraints and costs at the time (Costello, 1997).

The past decade has seen explosive growth in this field, with increases in computational power and affordability of digital systems effectively reducing barriers to technological manufacturing, consumer markets, required skills, and organizational needs (Westwood, 2002). In 2019, seven million commercial HMDs were sold and with sales projected to reach 30 million per year by 2023 (Statista, 2020). This mass consumer adoption has partly been due to a decrease in hardware cost and a corresponding increase in usability. These commercial systems provide a method for conveying 6-DoF information (position and rotation), while also learning from user behavior and movement. From these observations, we argue that the integration of iVR as a medium for guided physical healthcare may offer a cost-effective and more computationally adept option for exercise.

Reflecting back to Sutherland's vision of an ultimate display, we ask: *what would be the ultimate iVR system for physical rehabilitation?* If the sensation of physical reality can be simulated through computation, how might that reality best help the user with exercises and physical rehabilitation? From these questions, we posit that Sutherland's vision of the Ultimate Display requires augmentation to address a key area for healthcare: an intelligent perspective of how to best assist a user. In this paper, we explore these questions by reviewing immersive virtual reality as it intersects the fields of therapy, human behavior, and biofeedback. Immersive media affords a medium for enhancing the therapy and healthcare process. It establishes a mode for understanding human behavior, simulating perception, and providing physical assistance. Biofeedback provides a methodology for evaluating emotional response, a crucial element of mental health that is not often explored in healthcare. Given these key points, the rest of this introduction describes our motivation and goals in undertaking this study.

1.1. A Need for a More Efficacious Healthcare Medium With Physical Therapy

Physical inactivity leads to a decline of health, with significant motor degradation, a loss of coordination, movement speed, gait, balance, muscle mass, and cognition (Howden and Meyer, 2011; Sandler, 2012; Centers for Disease Control and Prevention, 2019). In contrast, the medical benefits of regular physical activity include prevention of motor degradation, stimulation of weight management, and reduction of the risk of heart disease and certain cancers (Pearce, 2008). While traditional rehabilitation has its merits, compliance in performing physical therapy may be limited due to high costs, lack of accessibility, and low education (Campbell et al., 2001; Burdea, 2003; Jack et al., 2010; Mousavi Hondori and Khademi, 2014; Centers for Disease Control and Prevention, 2019). These exercises also usually lack positive feedback, which is critical in improving compliance with physical therapy protocol (Sluijs et al., 1993). Taking these issues into consideration, some higher-tech initiatives associated with telemedicine, virtual reality, and robotics programs have been found to be more effective in promoting compliance than traditional paper-based and verbal instructions (Deutsch et al., 2007; Byl et al., 2013; Mellecker and McManus, 2014). These higher-tech exercise programs often use sensors to passively monitor a patient's status or to provide feedback so the action can be modified. They may also use actuators to assist the patient in completing the motion (Lindeman et al., 2006; Bamberg et al., 2008). Thus, technology may enable a patient to better follow their physical therapy program, aiding independent recovery and building on the progress made with the therapist. This raises the question of whether virtual environments in the form of iVR might be a suitable technology to address these issues.

Immersive virtual environments and the recent uptake of serious games have immense potential for addressing these issues. The ability to create stimulating programmable immersive environments has been shown to increase therapy compliance, accessibility, and data throughput (Mousavi Hondori and Khademi, 2014; Corbetta et al., 2015). Considerable success has been reported in using virtual environments for therapeutic intervention between psychological and physiological research. However, these systems have been mostly constrained due to cost and hardware limitations (Costello, 1997). For example, early 2000s head-mounted display systems had significant hardware constraints, such as low resolution and low refreshment rates, which led to non-realistic and non-immersive experiences that induced motion sickness (LaViola, 2000). Therefore, at that time, the potential use of immersive displays as a rehabilitation tool was quite limited.

These challenges are no longer as prevalent today: modern iVR systems have advanced technically and can now enhance user immersion through widening the field of view, increasing frame rate, leveraging low-latency motion capture, and providing realistic surround sound. These mediums are becoming ever more mobile and are now a part of the average consumer's entertainment experience (Beccue and Wheelock, 2016). As a result, we argue that now is the right time to consider these display mediums as a possible means of addressing the need for effective, cost-effective healthcare. It may be possible that for iVR to be used as a vehicle to augment healthcare to assist users in recovery by transforming the "fixing people" mentality (Seligman et al., 2002) of traditional rehabilitation into adventures in the virtual world that provide both meaningful enjoyable experiences and restorative exercise.

1.2. Review Goals

The goal of this paper is to survey the theory, application, and methodology of influential works in the field of immersive media for the purpose of exploring opportunities toward future research, with the ultimate aim of applying these technologies to engage physical rehabilitation. The subsequent sections of this paper provide a discussion of the following topics:

- the current state of academic research in utilizing iVR for physical rehabilitation and health;
- the behavioral theory behind the success of utilizing iVR;
- the applications of biofeedback and incorporating runtime user analysis in virtual environments;
- and bridging potential synergies between each of these areas toward applying them for future research.

This work will provide an overview of iVR for physical rehabilitation and health through an understanding of both past and current academic projects. We aim to provide an informative view on each of our goals as well as offering suggestions for how these concepts may be used to work toward an ultimate display of physical rehabilitation. We believe that this work will be of interest to interdisciplinary researchers at the intersection of immersive media, affective computing, and healthcare intervention.

1.3. Scope and Limitations

The term VR was coined long before the advent of recent immersive virtual reality (iVR) systems. This has led to differences in how the term "VR" is applied, and these differences can be seen within the existing literature. For the purposes of this review, we define niVR as non-immersive systems that utilize a monitor and allow user interaction through conventional means such as keyboards, mice, or custom controllers (Costello, 1997). VR systems that provide a head-mounted display (HMD) with a binocular omni-orientation monitor, along with appropriate three-dimensional spatialized sound, are categorized as iVR. Augmented reality (AR) systems employ virtual feedback by allowing the user to see themselves and their surroundings projected virtually onto a screen, usually in a mirror-like fashion (Assis et al., 2016). These systems are similar in how they present movement-based tasks with supplementary visual and auditory feedback, but differ in their interaction methods (Levac et al., 2016).

Our review focuses on iVR systems for physical rehabilitation, health, and games for health. We examine high-impact case studies, meta-reviews, and position papers from academia with an emphasis on research conducted in the past two decades. This paper provides a high-level overview of each of these areas and their implications for healthcare. However, we must acknowledge that immersive media, and many of the other concepts described in this paper, are rapidly changing fields. Many of the academic work and positions discussed in this paper are likely to change in the future as technology advances. With these considerations in mind, this paper provides a snapshot of these research areas from past to present and derives limitations and challenges from such to infer the need for future research in advancing an ultimate display for physical rehabilitation. We start by examining iVR for healthcare and rehabilitation.

2. IMMERSIVE VIRTUAL REALITY AND THERAPY

In the past two decades, there have been many publications and studies focusing on VR technologies for application in psychotherapy, physiotherapy, and telerehabilitation. Modern iVR technology is commonly known for its impact on enhancing the video gaming paradigm by deepening user involvement and leading to more dedicated interaction (Baldominos et al., 2015). The increased physical demands of these video gaming platforms have garnered interest for their potential in therapy through repetitive and quantifiable learning protocols (Salem et al., 2012). Early research suggests that the use of iVR systems is useful for psychological, physical, and telepresence therapy (Kandalaft et al., 2013; Straudi et al., 2017).

2.1. Psychological Therapy Applications

Psychological research has seen an increase in the use of iVR due to its ability to simulate realistic and complex situations that are critical to the success of laboratory-based human behavior investigations (Freeman et al., 2017). Some of these investigations include the successful reduction of pain through the use of stimuli in iVR. This has shown results equivalent to the effects of a powerful analgesic treatment, such as morphine, for burn victim wound treatment (Hoffman et al., 2011; Gromala et al., 2015). With the immersive capabilities of modern headsets, such as the HTC Vive and Oculus Rift, there has been an increase in studies reporting positive outcomes of iVR exposure therapies for post-traumatic stress disorder (Rothbaum et al., 2014; Morina et al., 2015), borderline personality disorder (Nararro-Haro et al., 2016), phobias (Grillon et al., 2006; Shiban et al., 2015), and schizophrenia (Rus-Calafell et al., 2014), as well as many other psychological therapies. This accelerated iVR use in psychological therapy is often attributed to the relationship between increased presence and emotion (Diemer et al., 2015; Morina et al., 2015). Increasing the number of meaningful stimuli that resonate with the users' engagement using iVR is a crucial factor in influencing user behavior and experience (Baños et al., 2004), and, with the price of computing devices and hardware decreasing, headsets are becoming more popular and immersive in doing so (Beccue and Wheelock, 2016; Statista, 2020). Thus, immersion through iVR can lead to greater emotional influence on the user and can incite the desired physiological responses by crafting a stimulating and engaging virtual environment (Chittaro et al., 2017). While this work shows great promise, the psychological application of iVR is still largely underdeveloped and lacking in terms of proven beneficial results. Similar results and benefits can also be seen with physical therapy interventions utilizing iVR.

2.2. Physiological Therapy Applications

Traditional forms of physical therapy and rehabilitation are based on therapist observation and judgment; this process can be inaccurate, expensive, and non-timely (Mousavi Hondori and Khademi, 2014). Many studies have indicated that iVR can be an effective tool in improving outcomes compared to conventional physical therapy (Lohse et al., 2014). Environments can be tailored to cue specific movements in real-time through sensory feedback via the vestibular system and mirror imagery to exemplify desired ranges of motion (Iruthayarajah et al., 2017). With the emergence of new immersive multimedia, iVR experiences with sight, sound, and touch can be integrated into rehabilitation. Studies have indicated that iVR intervention is useful in improving a variety of motor impairments, such as hemiparesis caused by Parkinson's disease, multiple sclerosis, cerebral palsy, and stroke (Iruthayarajah et al., 2017).

High repetitions of task-oriented exercises are critical for locomotive recovery, and user adherence to therapy protocol is imperative. iVR-based physical rehabilitation can induce adherence to therapy protocol as successfully as (and sometimes better than) human-supervised protocol due to the capabilities of multi-sensory real-time feedback (Corbetta et al., 2015). Games can be used to guide the user in their movements and provide mechanics to reward optimal exercises (Corbetta et al., 2015). Additionally, this multi-sensory, auditory, and visual feedback can further persuade users to exercise harder through increased stimuli. iVR-based physical rehabilitation also allows for increased quantitative feedback for both the user and the therapist. The capacity of modern iVR systems to implement three-dimensional motion tracking serves as an effective way to monitor progress during rehabilitation, allowing healthcare professionals to obtain a more in-depth view of each user's independent recovery (Baldominos et al., 2015).

Multiple reviews have been conducted consisting of hundreds of studies through the past decade, and have concluded that niVR is useful for motor rehabilitation (Cameirão et al., 2008; Saposnik et al., 2011; Mousavi Hondori and Khademi, 2014). Many of these studies have confirmed that the use of iVR results in significant improvements when compared to traditional forms of therapy (Corbetta et al., 2015; Iruthayarajah et al., 2017). These studies used Kinect, Nintendo Wii, IREX: Immersive Rehabilitation Exercise, Playstation EyeToy, and CAVE, as well as custom-designed systems. For a given treatment time, the majority of these studies suggested that video game-based rehabilitation is more effective than standard rehabilitation (Cruz-Neira et al., 1993; Lohse et al., 2014; Corbetta et al., 2015; Iruthayarajah et al., 2017). Subsequently, the physical rehabilitation communities have been enthusiastic about the potential to use gaming to motivate post-stroke individuals to perform intensive repetitive task-based therapy. Some games can combine motion capture as a way to track therapy adherence and progress. Despite these promising studies, technology at the time needed to improve in terms motion-tracking accuracy in order to become more effective, reliable, and accessible (Crosbie et al., 2007; Mousavi Hondori and Khademi, 2014). The existing research indicates that more work is needed to continue gaining a deeper understanding of the efficacy of iVR in rehabilitation (Cameirão et al., 2008; Dascal et al., 2017). These modern iVR headsets open up new opportunities for accessibility and affordability of treatment.

2.3. Telerehabilitation Applications

Telerehabilitation approaches provide decreased treatment cost, increased access for patients, and more quantifiable data for therapists (Lum et al., 2006). There have been various studies confirming the technical feasibility of in-home telerehabilitation, as well as an increase in the efficiency of these services (Kairy et al., 2013). In these studies, users generally achieve more significant results in rehabilitation due to the increased feedback from the telerehabilitation VR experience (Piron et al., 2009). Due to the mobile and computational nature of VR displays, these iVR telerehabilitation studies suggests that the usability and motivation of the rehabilitation treatment for the user can be sustained while reducing work for therapists and costs for patients (Lloréns et al., 2015).

2.4. Limitations of Current Studies for iVR Rehabilitation

While iVR has shown great promise from these studies, we must establish whether these HMDs and immersive displays are a truly beneficial medium. The cost of HMDs is reducing and commercial adoption is prevalent (Beccue and Wheelock, 2016). However, research into the effectiveness of iVR as a medium for rehabilitation is still inconsistent and is not often verified for reproducibility. An unfortunate commonality between these studies lies in a lack of reporting methodology, small or non-generalizable user sample sizes, not accounting for the novelty effect, and making blunt comparisons in terms of the effectiveness and usability of such systems. For example, in a review by Parsons et al., hundreds of studies addressing virtual reality exposure therapy for phobia and anxiety were reviewed in terms of affective functioning and behavior change. The biggest issue with Parsons's comparative review was a small sample size and a failure to account for the variety of factors that play into VR. The authors argue that Virtual Reality Exposure Therapy (VRET) is a powerful tool for reducing negative symptoms of anxiety, but could not directly calculate demographics, anxiety levels, phobia levels, presence, and immersion between these studies. While curating this review did provide an active snapshot into VRET usage in academia, it is arguable that the data from these studies may have been weak or biased due to the low sample sizes demonstrating positive results and the missing factors of usability for use beyond a single academic study (Parsons and Rizzo, 2008). A study by Jeffrey et al. examined twenty children who received distraction from IV treatment with two controls; iVR HMDs with a racing game as a distraction and a distraction-free treatment case. The results indicated that pain reduction was significant, with a four-fold decrease in facial pain scale responses in cases where iVR was used (Gold et al., 2006). This work positively supports the use of iVR HMDs as a medium for pain reduction, but also lacks a large sample size and provides a somewhat biased comparison of iVR. Is it not to be expected that any distraction of pediatric IV placement would reduce pain? Is iVR vs. no distraction a fair comparison to the general protocol for pediatric IV placement? What about the usage of a TV, or even an audiobook, against the iVR case? In another review by Rizzo et al., VRET was studied using an immersive display that showed veterans 14 different scenarios involving combat-related PTSD stimuli. In one trial, 45% of users were found to no longer test positive for PTSD after seven sessions of exposure. In another trial, more than 75% no longer tested positive for PTSD after 10 sessions. Most users reported liking the VR solution more than traditional exposure therapy (Rizzo et al., 2014). Again, this use of iVR for therapy focused on a small sample size and specific screening techniques, which must be taken into consideration when reviewing the results. Testing for PTSD change in this context only provides a snapshot of VR's effectiveness. Furthermore, the novelty effect (in the sense that the users are not acclimated to the system) may have a significant influence on the result. Given these points, what would happen when users have fully acclimated to this system—is the promise of VRET therapy demonstrated by Parsons et al. truly generalizable? Ultimately, the answer may lie in the direct need for more iVR rehabilitation studies to evaluate and transparently disseminate results between the iVR and niVR comparative norms. An ultimate display for physical rehabilitation with the ability to simulate almost any reality in instigating therapeutic goals may have much potential, but we must understand the behavioral theory behind iVR as a vehicle for healthcare.

3. IMMERSIVE VIRTUAL REALITY, BEHAVIOR, AND PERCEPTION

As discussed in the previous section, immersive media systems hold vast potential for synergizing the healthcare process. Rehabilitation research, including physical and cognitive work incorporating iVR-based interventions, has been on the rise in recent years. There is now the ability to create programmable immersive experiences that can directly influence human behavior. Conducting conventional therapy in a iVR environment can enable high-fidelity motion capture, telepresence capabilities, and accessible experiences (Lohse et al., 2014; Elor et al., 2018). Through gamification, immersive environments with commercial iVR HMDs, such as the HTC Vive, can be programmed to increase therapy compliance, accessibility, and data throughput by crafting therapeutic goals as game mechanics (Elor et al., 2018). However, what drives the success of iVR healthcare intervention? What aspects of behavioral theory can inform an optimal virtual environment that will assist users during their healthcare experiences? This section aims to explore and understand the theory behind the success of using iVR in healthcare.

3.1. The Benefits of Immersion

iVR provides a means of flexible stimuli through immersion for understanding human behavior in controlled environments. Immersion in a virtual environment can be characterized by the sensorimotor contingencies, or the physical interaction capability of a system (Slater, 2009). It attributes to how well the system may connect a user in iVR through heightened perception and ability to take action, also known as perceptual immersion (Skarbez et al., 2017). This is dependent on the number of motor channels and the range of inputs provided by the system in order to achieve a high fidelity of sensory stimulation (Bohil et al., 2011). Subsequently, perceptual immersion also opens an opportunity for psychological immersion (Skarbez et al., 2017), enabling users to perceive themselves to be enveloped by and a part of the environment (Lombard et al., 2000).

The success of iVR therapeutic intervention is often attributed to the influence of immersion in terms the ability to enhance the relationship between presence and emotion in an engaging experience, and the influence of this on overcoming adversity in task-based objectives (Morina et al., 2015). Immersion can be continuously enhanced through improving graphics, multi-modality, and interaction (Slater, 2009). Strong immersive stimuli through a iVR system, and the ability to provide a feeling of presence and emotion engagement in a virtual world, are key to influencing user behavior (Baños et al., 2004; Morina et al., 2015; Chittaro et al., 2017). Because of this, iVR can play an essential role in augmenting the physical therapy process through the benefits of immersion as it corresponds to a greater spatial and peripheral awareness (Bowman and McMahan, 2007).

Higher-immersion virtual environments were found to be overwhelmingly positive in treatment response (Miller and Bugnariu, 2016). The detachment from reality that is induced by immersion in a virtual world can reduce discomfort for a user, even as far as minimizing pain when compared to clinical analgesic treatments (Hoffman et al., 2011; Gromala et al., 2015). For example, one study found that an iVR world of playful snowmen and snowballs may reduce pain as effectively as morphine during burn victims' wound treatment (Mertz, 2019). Increasing the number of stimuli using iVR is a crucial factor in influencing user experience (Baños et al., 2004). With iVR systems becoming ever more affordable and accessible, these immersive environments are becoming available to the average consumer (Beccue and Wheelock, 2016).

3.2. Presence in the Virtual Environment

Given the benefits of immersion, from task-based guidance in spatial awareness to enabling psychological engagement, it is critical to quantify the effects of presence through immersion. Diemer et al. (2015) have suggested that presence is derived from the technological capabilities of the iVR system and is strengthened by the sense of the immersion of a virtual environment. "Presence" can be defined as the state of existing, occurring, and being present in the virtual environment, and it has been extensively modeled and quantified through past research. Schubert et al. (2001) have argued that presence has three dimensions: spatial presence, involvement, and realness. These dimensions are often quantified through a preliminary survey and cognitive scenario evaluation. Witmer and Singer (1998) have argued that presence is cognitive and is manipulated through directing attention and creating a mental representation of an Immersive Virtual Environment (iVE). Furthermore, Seth et al. (2012) have argued for the introspective predictive coding model of presence, which posits that presence is not limited to iVR but is "a basic property of normal conscious experience." This argument rests on a continuous prediction of emotional and introspective states, where the perceiver's reaction to the stimulus is used to identify success. For example, a fear stimulus as can be utilized during the prediction of emotional states, where the user compares the actual introspective state (fear and its systems) with the predicted emotional state (fear). A higher presence indicates successful suppression of the mismatch between the predicted emotional state vs. actual emotional state (Diemer et al., 2015). Thus, if the prediction of the fear stimuli is victorious over the mismatch of the user's actual reaction, this may indicate that they were happy, rather than in a state of fear (as was predicted). The idea that suppression of information in a VR experience is vital for presence and the inducing emotion is not new and was previously proposed by Schuemie et al. (2001). Seth et al. (2012) have emphasized that the prediction of emotional states from stimuli plays a crucial role in enabling an emotional experience. Parsons and Rizzo, (2008) research supports this claim; presence is regarded as a necessary mediator to allow "real emotions" to be activated by a virtual environment. However, Diemer et al. has cautioned that research has not yet clarified the relationship between presence and emotional experiences in iVR.

Moreover, quantifying presence is still primarily conceptualized through task-based methods (such as subjective ratings, questionnaires, or interviews), all of which are largely qualitative in nature. A debate between many of these presence theories is whether or not emotion is central to modeling presence. For example, Schubert et al.'s "spatial presence" or Slater's "place illusion" do not require emotion as a prerequisite for presence, which is unlike Diemer's hypothesis of emotion connecting presence and immersion. Given that physical health and recovery has been heavily linked to emotional states (Salovey et al., 2000; Richman et al., 2005), we consider Diemer at al.'s model of presence. Therefore, to effect presence in a virtual environment, there is a need of quantifying emotion. How does one model emotion in this regard, or even quantify it?

3.3. Emotion and Virtual Environments

Quantifying the human emotional response to media has been the topic of much debate in academia. Ekman (1992), a pioneer of emotion theory, argued that there are six basic emotions: anger, fear, sadness, enjoyment, disgust, and surprise. He argued that there are nine characteristics of emotions: they have universal signals, they are found between animals, they affect the physiological system (such as the nervous system), there are universal events which invoke emotion, there is coherence in emotional response, they have rapid onset, they have a brief duration, they are appraised automatically (subconsciously), and their occurrence is involuntary (Ekman, 1992). Ekman's theory does not dismiss any affective phenomena, but instead organizes them to highlight the distinction, based on previous research (in the fields of evolution, physiology, and psychology) between the field and his previous work. His theory also provides a means of quantifying emotions using these principals; it offers a theoretical framework for constructing empirical studies to understand affective states as well as basic emotions (Ekman, 1992). Ekman's basic emotions were found and identifiable in media such as music (Mohn et al., 2011) and photos (Collet et al., 1997).

Since the early 2000s, researchers have examined how technology can extend, emulate, and understand human emotion. Picard (2000), the pioneer of affective computing, has expanded upon theories such as Ekman's to build systems that understand emotion and can communicate with humans emotionally. This had lead numerous findings and demonstrations of systems that demonstrate discrete models (including Ekman's basic emotion model, appraisals models, dimensional models, circuit models, and component models) for quantifying emotional response (Picard, 2000; Kim, 2014). Moreover, numerous machine learning methods have been demonstrated as emotion inference algorithms, such as classification, artificial neural networks, support vector machines, k-nearest neighbor, decision trees, random forests, naive Bayes, deep learning, and various clustering algorithms (Kim, 2014).

With Diemer et al.'s model, emotional engagement may enhance presence to assist the user in an iVE task. Thus, it is useful to quantify a user's emotional response in an iVE. Many studies have examined sense signals and classified patterns as an emotional response from the Autonomic Nervous System. In relation to the basic emotions, Collet et al. (1997) have observed patterns in skin conductance, potential, resistance, blood flow, temperature, and instantaneous respiratory frequency through the use of six emotion-inducing slides presented to 30 users in random order. Through the use of questionnaires, Meuleman and Rudrauf (2018) found that appraisal theory induced the highest emotional response with the HTC Vive iVR System. Liu et al. have utilized real-time EEG-based emotion recognition by applying an arousal-valence emotion model with fractal dimension analysis (Liu et al., 2011) with 95% accuracy along with the National Institute of Mental Health's (NIMH) Center for Study of Emotion and Attention (CSEA) International Affective Picture System (IAPs) (Lang et al., 1997). One of the most widely used metrics for emotion evaluation is the NIMH CSEA Self-Assessment Manikin (SAM) (Bradley and Lang, 1994). Waltemate et al. (2018) used SAM to evaluate emotion concerning the sense of presence and immersion in embedded user avatars with 3D scans through an iVR social experience. SAM enables the evaluation of dimensional emotion (through quantifying valence, arousal, and dominance) by using a picture-matching survey to evaluate varying stimuli. It has been validated for pictures, audio, words, event-related potentials, functional magnetic resonance imaging, pupil dilation, and more (Bradley and Lang, 1994; Lang et al., 1997; Bynion and Feldner, 2017; Geethanjali et al., 2017).

In addressing emotional experiences that influence presence, or a user's sense of "being in" an iVE, we must consider what influences these experiences. Broadly, the majority of research turns to human perception to answer this question. Previous psychological research on threat perception, fear, and exposure therapy implies a relationship between perception and emotion. Perception influences emotion and presence in an iVE, which enables a controlled environment for identifying the most relevant aspects of each user's emotional experience (Baños et al., 2004). The association between perception and conceptual information in iVR must also be considered, as this can play a crucial role in eliciting emotional reactions. For behavior research focusing on areas such as fear, anxiety, and exposure effects, it is vital that iVR is able to induce emotional reactions leading presence and immersion (Diemer et al., 2015). This can be achieved by adjusting perceptual feedback of a user's actions through visual cues, sounds, touch, and smell to trigger an emotional reaction. This goes two ways, in the sense that iVR allows the consideration of how perception can be influenced by iVR itself while also enabling emotional engagement. Therefore, researchers can dissociate perceptual and informational processes as controlled conditions to manipulate their studies in unique ways using iVR (Baños et al., 2004). Given that researchers have found ways to model and influence perception for presence and emotion, what has been done in iVR?

3.4. Human Perception and Multi-Sensory Displays

Human perception appears to be the ultimate driver of user behavior. Yee and Bailenson's (2007) Proteus effect has demonstrated how both self-representation and context in a virtual environment can be successfully influenced via iVR HMDs. The way we perceive the world around us—through our expectations, self-representation, and situational context—may influence how we act and how we approach behavioral tasks. Human perception is reliant on multimedia sensing, such as processing sight, sound, feel, smell, and taste (Geldard et al., 1953). This is problematic because the majority of published research on iVR does not account for this; many studies focus on a singular modality such as a sight or sound, and only occasionally connect sight, sound, and feel. However, with modern advances in commercially available hardware, all senses except for taste have the potential to be controlled in a virtual environment.

3.4.1. Stimuli and Perception

Exploring new input modalities for iVR in physical rehabilitation may help discover new and effective approaches for treatment experience. For example, there have been many studies that have examined how haptic feedback can communicate, help recognize, and inform pattern design for emotions. Bailenson et al. (2007) examined how interpersonal touch may reflect emotional expression and recognition through a hand-based force-feedback haptic joystick. They found that users were able to both recognize and communicate emotions beyond chance through the haptic joystick. In a study by Mazzoni and Bryan-Kinns (2015), the design and evaluation of a haptic glove for mapping emotions evoked by music were found to reliably convey pleasure and arousal. Bonnet et al. (2011) found that facial expression emotion recognition was improved when utilizing a "visio-haptic" platform for virtual avatars and a haptic arm joystick. Salminen et al. (2008) examined the patterns of a friction-based horizontally rotating fingertip stimulator for pleasure, arousal, approachability, and dominance for hundreds of different stimuli pairs. Fingertip actuation indicated that a change in the direction and frequency of the haptic stimulation led to significantly different emotional information. Obrist et al. (2015) demonstrated that patterns in an array of mid-air haptic hand stimulators map onto emotions through varying spatial, directional, and haptic parameters. Miri et al. (2020) examined the design and evaluation of vibrotactile actuation patterns for breath pacing to reduce user anxiety. The authors found that frequency, position, and personalization are critical aspects of haptic interventions for social-emotional applications.

Many prior studies have also found that olfactory echoing principle of universal emotions. Fox (2009) has examined the human sense of smell and its relationship to taste, human variation, children, emotion, mood, perception, attraction, technology, and related research. Sense of smell is often dependent on age (younger people outperform older people), culture (western cultures differ from eastern cultures), and sex (women outperform men). However, other studies suggest that sense of smell mainly depends on a person's state of mental and physical health, regardless of other factors. Some 80-year-olds have the same olfactory prowess as 20-year-olds, and a study from the University of Pennsylvania showed that people who are blind do not necessarily have a keener sense of smell than sighted people (Fox, 2009). It appears to be possible to "train" one's sense of smell to be more sensitive. This poses a problem for researchers, as some subjects in repetitive experiments become skilled in this (i.e., the weight of scent differ for people depending on their sensitivity). Subsequently, Fox (2009) has argued that "the perception of smell consists not only of the sensation of the odors themselves but of the experiences and emotions associated with sensations." These smells can evoke strong emotional reactions based on likes and dislikes determined by the emotional association. This occurs because the olfactory system is directly connected with an ancient and primitive part of the brain called the limbic system where only cognitive recognition occurs. Thus, a scent may be associated with the triggering of deeper emotional responses. Similar to the Proteus effect (Yee and Bailenson, 2007), our expectations of an odor influence our perception and mood when encountering the stimulus (Fox, 2009).

In terms of perception, positive emotions are indicated with pleasant fragrances and can affect the perception of other people (such as attractiveness of perfume and photographs). Unpleasant smells tend to lead to more negative emotions and task-based ratings (such as when viewing a picture or a completing survey of pleasant or unpleasant odors). General preferences for smells exist (i.e., that the smell of flowers is pleasant and that the smell of gasoline or body odor is unpleasant). Some fragrances, such as vanilla, are universally perceived as pleasant (which is why most perfumes use vanilla). Perfume makers have also shown that appropriate use of color can better identify our liking of fragrance (Fox, 2009). This is supported by the work of Hirsch and Gruss (1999), who explored how olfactory aromas can be quantified to demonstrate arousal. They explored 30 different scents via wearable odor masks with 31 male volunteers. By measuring penile blood flow, the authors found that every smell produced an increase of penile blood flow when compared to no odor, and that pumpkin pie and lavender (which, according to Fox, is considered a universally pleasant scent) produced the most blood flow, with a 40% increase (Hirsch and Gruss, 1999). There appear to be universal smells that are coherent across different demographics, similar to Ekman's argument for universal emotions shared by different races, animals, and sexes (Ekman, 1992; Fox, 2009). An ultimate display that could utilize these smells and adapt to each user's individual preferences by understanding their presence and emotion could be useful in both eliciting an engaging medium of therapy and discovering new universal stimuli.

3.4.2. On Multi-Modal Immersive Virtual Reality Environments

Many researchers have started to recognize and explore the potential of multi-modality iVR interfaces. In an exploratory study by Biocca et al. (2001), the authors concluded that presence may derive from multi-modal integration, such as haptic displays, to improve user experiences. Bernard et al. (2017) showcased an Arduino-driven haptic suit for astronauts to increase embodied situation awareness, but no evaluation was reported. Goedschalk et al. (2017) examined the potential of the commercially available KorFX vest to augment aggressive avatars, but found an insignificant difference between the haptic and non-haptic conditions. And, Krogmeier et al. (2019) demonstrated how a bHaptics Tactisuit vest can influence greater arousal, presence, and embodiment in iVR through a virtual avatar "bump." The authors found significantly greater embodiment and arousal with full vest actuation compared to no actuation. However, this study only examined a singular pattern and one set stimuli.

Numerous examples can also be seen with thermal actuation, haptic retargeting, and olfactory input. For example, Wolf et al. (2019) and Peiris et al. (2017) explored thermal actuation embedded in iVR HMD facial masks and tangibles which increased enjoyment, presence, and immersion. Doukakis et al. (2019) evaluated a modern system for audio-visual-olfactory resource allocation with tri-modal virtual environments which suggested that visual stimuli is the most preferred for low resource scenarios and aural/olfacotry stimuli preference increases significantly when budgeting is available. Warnock et al. have found that multi-modality notifications through visual, auditory, tactile, and olfactory interfaces were significant in personalizing the needs and preferences of home-care tasks for older adults with and without disability (McGee-Lennon and Brewster, 2011; Warnock et al., 2011). Azmandian et al. (2016) used haptic virtual objects to "hack" real-world presence by shifting the coordinates of the virtual world, leading users to believe that three tangible cubes lay on a table when in reality there was only one cube. Olfactory inputs have been found to be incredibly powerful in increasing immersion and emotional response, such as in Ischer et al.'s (2014) Brain and Behavioral Laboratory Immersive Oder System, Aiken and Berry's (2015) review of olfaction for PTSD treatment, and Schweizer et al.'s (2018) application of iVR and olfactory input for training emergency response. Dinh et al. (1999) demonstrated that multi-sensory stimuli for an iVR virtual office space can increase both presence and spatial memory from a between-subjects factorial user study that varied level of visual, olfactory, auditory, and tactile information. These systems have shown great promise in personalizing systems with the capability to rapidly adapt to smells in an iVR environment. Beyond these theories and proposed systems, there are many limitations and challenges to keep in mind when translating these theories into applied environments.

3.5. Limitations of Current Studies for iVR Behavior and Perception

Immersion, presence, and emotion are critical in influencing an engaging, motivating, and beneficial iVR therapy. However, these themes are not analyzed in iVR therapy studies as standard. This may be primarily due to a lack of uniform quantification of these areas. However, there are many surveys and sensing techniques used to quantify biofeedback, such as the NIMH CSEA SAM and valence-arousal models. Even when studies incorporate such considerations, sample sizes are usually small and methodology is not always transparent. A gold standard can be seen with the NIMH CSEA Self-Assessment Manikin (Bynion and Feldner, 2017; Geethanjali et al., 2017), for which affect is validated using a stimuli database that has been pre-validated by hundreds of participants. There may be a clear benefit in releasing the iVR stimuli evaluated through the ultimate display to create an international affective database for cross-modal virtual reality stimuli.

The user's understanding of how to perform therapy exercises, as well as their commitment to performing them for the duration of the therapy, is critical to ensure effectiveness of rehabilitation. The emotional response generated by an immersive experience influences user engagement and may motivate patients to continue with the objectives of the virtual experience (Chittaro et al., 2017). Therefore, we ask: *how might we quantify the success of iVR stimuli toward affecting a users emotional engagement?* This leads us to the next section, in which we discuss how understanding the increasing availability of biometric sensors and biofeedback devices for public use may help us find answers to these questions (Soares et al., 2016).

4. IMMERSIVE VIRTUAL REALITY AND BIOFEEDBACK

This section aims to identify the theory and usage of biofeedback through a variety of sensory modalities for immersive media and behavioral theory. Biofeedback devices have gained increasing popularity, as they use sensors to gather useful, quantifiable information about user response. For example, the impedance of the sweat glands, or galvanic skin response (GSR), has been correlated to physiological arousal (Critchley, 2002; Boucsein, 2012). This activity can be measured through readily available commercial GSR sensors, and has been explored by researchers to measure the arousal created by media such as television, music, and gaming (Rajae-Joordens, 2008; Salimpoor et al., 2009). Different types of iVR media may affect biofeedback performance. Cameiro et al. analyzed niVR-based physical therapy that uses biofeedback to adapt to stroke patients based on the Yerkes-Dodson law (Cameirao et al., 2009) or the optimal relationship between task-based performance and arousal (Cohen, 2011). By combining heart rate (HR) with GSR, game events and difficulty were quantitatively measured for each user to evaluate optimal performance. Another example can be seen in the work of (Liu et al., 2016), in which GSR alone achieved a 66% average emotion classification accuracy for users watching movies. Combined with GSR, HR can indicate the intensity of physical activity that has occurred. There is definite potential in evaluating the GSR and HR of each user to determine the intensity of the stimuli using different systems of iVR. However, GSR and HR are not the only biometric inputs that could be potentially leveraged when understanding an immersive experience.

In another biofeedback modality, commercially available electroencephalography (EEG) sensors have shown great promise in capturing brain activity and even in inferring emotional states (Ramirez and Vamvakousis, 2012). Brain-computer Interfaces (BCI) incorporating EEG devices have become ever more affordable and user-friendly, with computational techniques for understanding user engagement and intent in medical, entertainment, education, gaming, and more (Al-Nafjan et al., 2017). Based on a review of over 280 BCI-related articles, Al-Nafjan et al. (2017) have argued that EEG-based emotion detection is experiencing booming growth due to advances in wireless EEG devices and computational data analysis techniques such as machine learning. Accessible and low-cost BCIs are becoming more widely available and accurate in the context of both medical and non-medical applications. They can be used for emotion and intent recognition in entertainment, education, and gaming (Al-Nafjan et al., 2017). When compared with 12 other biofeedback experiments, studies that used EEG alone were able to reach 80% max recognition (Goshvarpour et al., 2017). Arguably, the most considerable challenges of BCI are costs, the impedance of sensors, data transfer errors or inconsistency, and ease of use (Al-Nafjan et al., 2017; Goshvarpour et al., 2017).

Even with these challenges, EEG has been successfully used to as a treatment tool for understanding conditions like attention deficit/hyperactivity disorder (ADHD), anxiety disorders, epilepsy, and autism (Marzbani et al., 2016). Brain signals that are characteristic of these conditions can be analyzed with EEG biofeedback to serve as a helpful diagnostic and training tool. Sensing apparatus can be coupled with interactive computer programs or wearables to monitor and provide feedback in many situations. By monitoring levels of alertness in terms of average spectral power, EEG can aid in diagnosing syndromes and conditions like ADHD, anxiety, and stroke (Lubar, 1991). Lubar et al. (1995) used the brainwave frequency power of game events to extract information about reactions to a repeated auditory stimulus, and have demonstrated significant differences between ADHD and non-ADHD groups. Through exploring different placements and brainwave frequencies of EEG sensors across a user's scalp, different wavebands can be used to infer the emotional state and effect of audio-visual stimuli (Deuschl et al., 1999). For example, Ramirez and Vamvakousis (2012) used the alpha and beta bands to infer arousal and valence, respectively, which are then mapped to a two-dimensional emotion estimation model. With these examples in mind, how does one quantify brainwaves for emotional inference?

4.1. Brainwaves as a Means of Studying Emotional Intelligence

Hans Berger, a founding father of EEG, was one of the first to analyze these frequency bands of brain activity and correlate them to human function (Haas, 2003; Llinás, 2014). The analysis of different brainwave frequencies has been correlated to different psychological functions, such as the 8–13 Hz Alpha band relating to stress (Foster et al., 2017), the 13–32 Hz Beta band relating to focus (Rangaswamy et al., 2002; Baumeister et al., 2008), the 0.5–4 Hz Delta band relating to awareness (Walker, 1999; Hobson and Pace-Schott, 2002; Iber and Iber, 2007; Brigo, 2011), the 4–8 Hz Theta band relating to sensorimotor processing (Green and Arduini, 1954; Whishaw and Vanderwolf, 1973; O'Keefe and Burgess, 1999; Hasselmo and Eichenbaum, 2005), and the Gamma band of 32–100 Hz related to cognition (Singer and Gray, 1995; Hughes, 2008; O'Nuallain, 2009). These different frequencies may prove fruitful in quantifying the effects of virtual stimuli during iVR based physical therapy, taking into account the fact that signals may be noisy due to other biological artifacts and must be handled carefully (Vanderwolf, 2000; Whitham et al., 2008; Yuval-Greenberg et al., 2008). For example, alpha activity is reduced with open eyes, drowsiness, and sleep (Foster et al., 2017); increases in beta waves have been suggesting for active, busy, or anxious thinking and concentration (Baumeister et al., 2008); delta activity spikes with memory foundation (Hobson and Pace-Schott, 2002) such as flashbacks and dreaming (Brigo, 2011); theta activity increases when planning motor behavior (Whishaw and Vanderwolf, 1973) path spatialization (O'Keefe and Burgess, 1999) memory, and learning (Hasselmo and Eichenbaum, 2005); and gamma shows patterns related to deep thought, consciousness, and meditation (Hughes, 2008).

Additionally, there are many methods for evaluating and classifying emotions with brainwaves. Eimer et al. (2003) used high-resolution EEG sensing to analyze the processing of Ekman's six basic emotions via facial expression during P300 event-related potential analysis (ERP). Emotional faces had significantly different reaction times from neutral faces (supporting the rapid onset of emotion Ekman's principle). The authors concluded that ERP facial expression effects gated by spatial attention appear inconsistent, however, ERP effects are directly due to Amygdala activation, they also conclude that ERP results demonstrate facial attention is strongly dependent on facial expression, and that the six basic facial expressions with emotions were strikingly similar (Eimer et al., 2003). ERPs are an effective way to quantify EEG brainwave readings for emotional analysis, but they are not always reliable. However, they can accurately gauge from an arousal response by looking at a P300 window of revealing stimuli. These techniques open opportunities for estimating emotion through multiple biofeedback modalities.

Researchers have combined these EEG interfaces with other forms of multi-modal biometric data collection such as GSR and HR to increase the inference of affective response. By combining GSR with HR and EEG, researchers have been able to increase the accuracy of emotion recognition (Liu et al., 2016; Goshvarpour et al., 2017). Other niVR based games have successfully incorporated the use of these biofeedback markers to determine physiological response (Cameirao et al., 2009; Soares et al., 2016). However, there is a lack of studies exploring these biometrics with iVR and physical therapy, such as the one described in this paper. This is particularly true in the case of examining long-term use beyond the novelty period and allowing for user acclimatization to the experimental environment. With such limitations in mind, it is possible that these effects and psychological responses could be quantitatively measured through combining active EEG sensing with the flexible stimuli of iVR gameplay. In the light of this, what has been done to bridge biofeedback to iVR?

4.2. Biofeedback Systems Utilized With Virtual Reality

The closest experience (albeit not immersive) to the proposed ultimate display augmentation for rehabilitation discussed in this paper can be seen in i Badia et al.'s work on a procedural biofeedback-driven nonlinear 3D-generated maze that utilized the NIMH CSEA International Affective Picture System. VR mental health treatment has seen extensive exploration and promising results over the past two decades. However, most of the experiences are not personalized for treatment, and more personalized treatment is likely to lead to more successful rehabilitation. i Badia et al. (2018) has argued for the use of biofeedback strategies to infer the internal state of the patient state. Users navigated a maze where the visuals and music were adapted according to emotional state (i Badia et al., 2018). The framework incorporated the Unity3D game engine in a procedural content generation through three modules of real-time affective state estimation, event trigger computation, and virtual procedural scenarios. These were connected in a closed-loop during runtime through biofeedback, emotion game events, and sensing trigger events. The software architecture uses any iVR medium and runs the Unity application with a separate process for data acquisition via UDP protocol, which was published and shared as a Unity plugin (i Badia et al., 2018). Overall results indicated significance for anger, fear, sadness, and neutral (in Friedman analysis), and a Self-Assessment Manikin Indicated significant feelings of pleasantness associated with the experience. However, the game was not explored using an immersive medium (instead, a Samsung TV was used), varying intensity was not explored, and control factors were random to each user, which may have influenced results (i Badia et al., 2018).

Immersive experiences exploring low-cost commercial biofeedback devices have been also been presented, although methodology has not been fully disseminated. Redd et al. (1994) found that cancer patients during Magnetic Resonance Imaging responded with a 63% decrease in anxiety with heliotropin (a vanillalike scent) with humidified air when compared to a odorless humidified air alone. Expanding upon this work, Amores et al. (2018) utilized a low-cost commercial EEG device, a brain-sensing headband named Muse 2 (InteraXon, 2019), with an olfactory necklace and immersive virtual reality for promoting relaxation. By programming odor to react to alpha and theta EEG activity within iVR, users demonstrated increases of 25% physiological response and reported relaxation when compared to no stimulus. This may validate the effectiveness of combining iVR with olfactory input, as well as the ability to quantify mental state through physiological changes through low-cost, low-resolution commercial EEG.

In another example, Abdessalem et al. compared mental activity of EEG recordings to the International Affective Picture System for a serious game named "AmbuRun." Users entered an iVR game in which they had to carry a patient in an ambulance to the hospital and drive it through traffic. They evaluated the game with 20 participants, and the difficulty adapted to each user so that higher frustration led to more traffic (Abdessalem et al., 2018). The authors identified significant results; 70% of players reported that the game was harder when they were frustrated, while only 15% said they did not notice any change in difficulty. However, this study does not share baseline EEG activity results, nor does it explain the adaptive difficulty algorithms that were used (Abdessalem et al., 2018). Other examples relating biofeedback and iVR can be found in the work of Marín-Morales et al. (2018), who examined EEG and heart rate variability with portable iVR HMDs to elicit emotions by exploring 3D architectural worlds. Krönert et al. (2018) developed a custom headband that recorded BVP, PPG, and GSR while adults completed various games in learning environments. Van Rooij et al. (2016) developed a game that displayed diaphragmatic breathing patterns in children with the aim of reducing in-game anxiety, and was able to get users to reverse panic attacks. Again, while all these results were highly promising in incorporating biofeedback techniques to augment iVR user experiences, they were also lacking in many areas.

4.3. Limitations of Current Studies for iVR Biofeedback

A large amount of work has been done independently in the biofeedback field in terms of methods of sensing mental activity, and there is now a plethora of sensing methods. Some games have been created incorporating biofeedback with promising results. However, these studies are often vague and do not publish stimuli or demos beyond what is written in the paper. In this literature review, we have found that most of these biofeedback games are not multi-modal sensing and thus do not account for any low-resolution sensing or movement artifacts from gameplay through sensor fusion (i.e., HR and GSR could be used with in-game behavior to cross-validate physiological signal change during therapy with EEG sensing). Additionally, the majority of these studies do not incorporate runtime feedback from the user themselves (beyond pre- or post-test surveys). Quantifying emotion is usually done either solely through biofeedback and emotion estimation, or post-test surveys, but never both during runtime. It is possible that biofeedback emotional estimation combined with embedded gameplay surveys may be a way to better objectively measure presence, as long as immersion is not broken when queried for survey response.

Additionally, these studies are often not conducted with multi-modal stimuli. Human perception is inherently multi-modal, and perhaps emotional response may become more accurate when utilizing multiple human senses beyond audio and visual stimuli. What happens when we factor in smell and touch while collecting biofeedback measures within iVR? As with the other limitations discussed in the previous two sections, much of this work is not disseminated beyond the papers themselves [with the exception of i Badia et al.'s (2018) published biofeedback plugin]. Future researchers can address these limitations by fully disseminating their methodology and algorithms in their work, and such aspects should be transparent toward the design and evaluation of immersive media with biofeedback.

5. AN ULTIMATE DISPLAY FOR PHYSICAL REHABILITATION

We dedicate this section to expand upon the current literature review and bridge the discussions in the previous sections on immersive virtual reality, rehabilitation, behavioral theory, and biofeedback. In the previous sections, we discussed how the newfound commercial adoption of iVR devices and the affordability of biofeedback devices may lead to new opportunities for adaptive experiences in healthcare that are feasible for the average consumer. iVR-based therapy from psychological, physiological, and telepresence applications have shown great promise and great potential. The theory and success behind iVR as a medium for healthcare intervention is driven by immersion and its relationship with presence and emotion. Because presence and emotion tend to be subjective, quantification of their measures is not always reproducible. However, many quantification methods exist, ranging from a sensing algorithmic approach to a variety of validated surveys. The current literature review has found that more work must be done to provide clear guidelines, universal iVR stimuli to evaluate affect, and an environment that factors multi-modal sensing and stimulation for presence and emotion. These items may address a need for a controllable multi-modal immersive display that can factor in physical and emotional intelligence through both qualitative and quantitative biofeedback.

5.1. Augmenting the Ultimate Display

To bridge the many academic works that we have surveyed, we consider a theoretical framework toward augmenting the ultimate display for rehabilitation. Such an augmentation would utilize the capabilities of a controlled iVE and quantifying emotion both through biofeedback (i.e., heart rate, sweat glands, and brainwaves) while also using in-game surveys to measure the user's self-perception and emotional state. The environment would factor in human perception and emotion through multiple co-dependent senses rather than a single sense. This could be achieved via olfactory modules, haptic feedback vests, and iVR HMDs. The system must account for pre-gameplay states and develop a baseline emotion profile for each user; this could be done by asking the user to relax for a set period of time while in the display in order to calibrate biofeedback sensors. With such a profile, we could examine how biofeedback changes occur when the user is presented with varying stimuli during exercise. The system may follow the effects of physical rehabilitation performance in comparison to biofeedback response and presented stimuli. By factoring in these metrics, we may be able to provide an iVR healthcare experience that adapts to each user's individual response and preferences.

This augmented display would equate to a sandbox controlled virtual environment to assist in the therapy process by enabling users to explore new attitudes, modulate cognitive biases, and examine behavioral responses. Through these multi-modal sensory and motor simulations, researchers could craft experiences to assist in therapeutic engagement, and quantify or adapt the experience through biofeedback during runtime. Our vision for this augmented ultimate display comes from the synergy of three components: immersive media, biofeedback, and wearable robotics. **Figure 1** demonstrates these mediums as inputs to augment the therapy process and show how they bring about emotional intelligence, physical intelligence, and adaptability.

As discussed in the previous sections, many components of this proposed augmentation have been rigorously researched independently within their respective fields. The synergies of these areas have the potential to produce emotional, physical, and adaptive intelligence from the interdisciplinary combination of these mediums. Nevertheless, these concepts are often not applied to healthcare. Some emergent research, as discussed in the previous sections [such as the work of i Badia et al.'s (2018)], has explored synergies between these areas, but these have not been fully demonstrated in healthcare or rehabilitation. Given the potential that immersive media has shown in therapy and rehabilitation, these fields and their synergies should be explored as one. This is necessary to advance the field of immersive media for healthcare and to fully understand how an ultimate display augmented for rehabilitation can be met. The center of **Figure 1** represents this vision; a display in which the very world the user performs their rehabilitation in can adapt its difficulty and game mechanics to motivate and guide them through their emotional response through immersive computational media. Such a display would explore the limits of modeling a person's emotional reaction, mental perception, and physical ability, while also applying rehabilitation theory in a quantifiable and controlled environment. Just as the moon influences the tide, perhaps this display could influence our emotional "tides" to best perform rehabilitative tasks by influencing our perception for the better. The core elements of this biometric infused cyber-physical approach to immersive media in rehabilitation are illustrated in **Figure 1**.

This review examined how iVR can be a powerful tool in reducing discomfort and pain. As in the case of SnowWorld, created at University of Washington's HITLab, the experience demonstrated that iVR can be as effective as morphine in reducing pain for burn victims (Gromala et al., 2015). Much of this success can be attributed to the benefits and affordances of immersion (Bowman and McMahan, 2007; Slater, 2009; Diemer et al., 2015; Skarbez et al., 2017). Therefore, the augmented ultimate display would need to enable the crafting of virtual worlds with high levels of presence and emotional engagement to assist user perception in overcoming adversity experienced in rehabilitation (such as pain and discomfort). One example to explore this may be readily feasible by augmenting the NIMH International Affective Databases (IAD) (Lang et al., 1997). Researchers could extend these existing stimuli with multi-modality and evaluate user experience through biofeedback. Additionally, through utilizing the capabilities of a controlled iVE, emotion could be accurately quantified through both employing biofeedback while also using in-game surveys to measure the user's self-perception and emotional state. This data might be further explored to adapt both the immersive media stimuli and the level of assistance. For example, such an experience may allow researchers to build a baseline affective dataset for each user that could be applied to other immersive healthcare experiences with iVR. Similar emotional states from this baseline experience can be used to predict emotional response in order to adjust game difficulty and assist users with physical movement. Through this process, we may be able to create the ultimate behavioral sandbox for quantifying emotion during behavioral tasks and collect profiles to be applied to runtime physical therapy environments that can account for emotional intelligence during gameplay.

5.2. The Ultimate Display as a Rehabilitation Toolbox for Task-Based Experiences

The development of an augmented ultimate display for rehabilitation may have broader impacts in the field of healthcare research. To illustrate some of the many theories that this system could explore, we share the following for consideration:

- Perception theory indicates that human perception is the composition of parallel senses of sight, hear, smell, feel, and taste, all of which influence behavior presence (Chalmers and

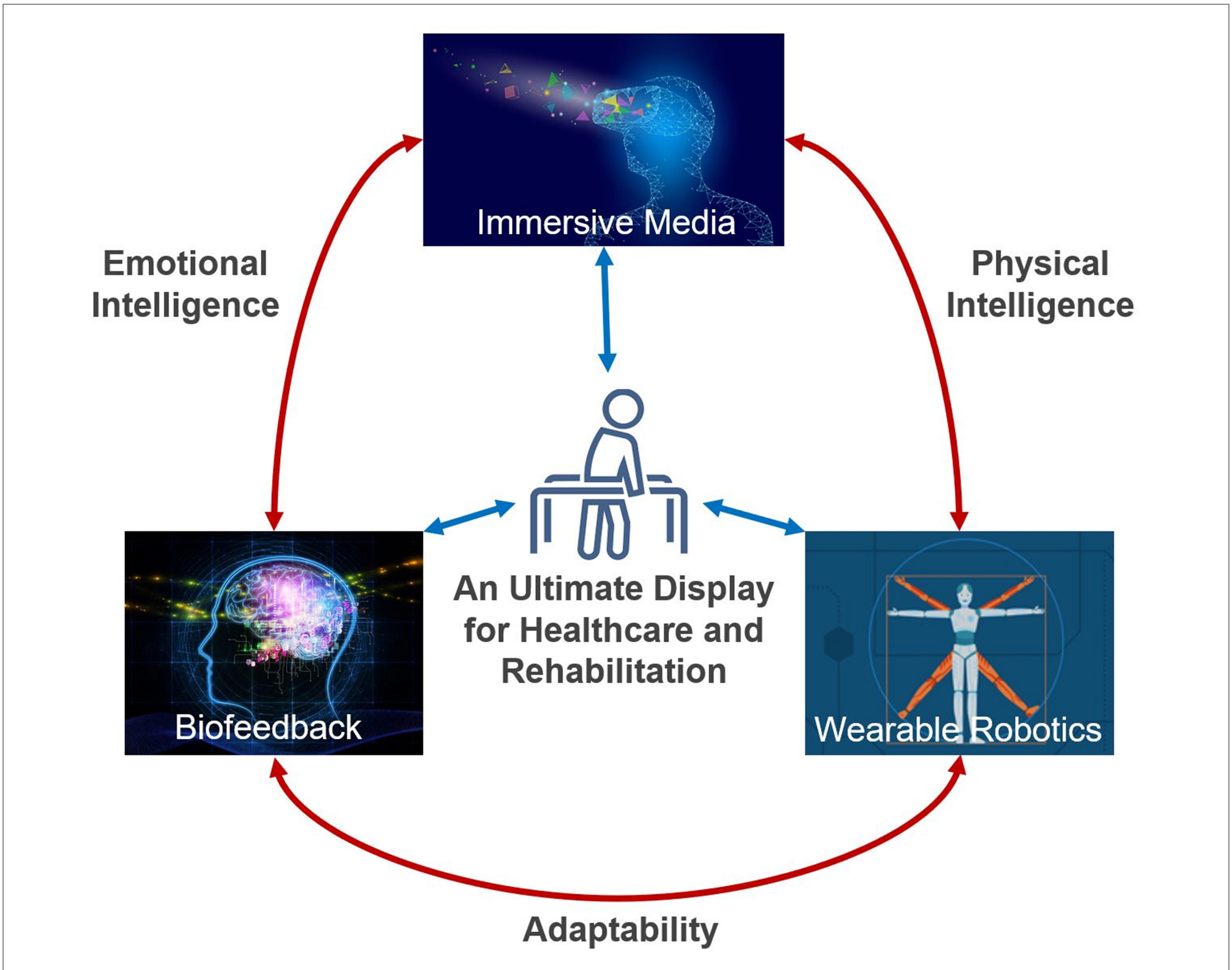

FIGURE 1 | Components of the theoretical ultimate display augmented for rehabilitation. Areas and some of their synergies through immersive media, wearable robotics, and biofeedback. Elements of wearable robotics enable automated tracking of user progression. Physical intelligence examples include haptic stimulation, physical assistance, and positional sensing informed between the virtual experience and the wearable. Emotional intelligence examples include personalizing iVR stimuli by arousal response and calibrating the difficulty of iVR therapy based on heart rate. Adaptability examples include adjusting the physical assistance of wearable robotics and allowing for biometric input modalities to enable users of mixed ability to participate in the virtual experience.

Ferko, 2008). Subsequently, a multi-sensory iVR experience should induce more significant immersion with affordances for presence and emotional response (Bowman and McMahan, 2007; Slater, 2009; Diemer et al., 2015; Skarbez et al., 2017). If this is true, perhaps we can create better iVR experiences for higher therapy engagement, compliance, and satisfaction.

- The Yerkes-Dodson Law states that, for any behavioral task, there is an optimal level of arousal to induce the optimal level of performance (Cohen, 2011). This law is one of the most frequently cited cognitive psychology theories but has never been verified (Teigen, 1994). If we can quantify arousal with the ultimate display by combining biofeedback sensing with in-game micro surveys, we may be able to verify the relationship between arousal and task-performance. If this is true, we may be able to create optimal stimuli to assist users in overcoming adversity within their therapy regimen.
- Csikszentmihalyi's Flow Theory suggests that total engagement in an activity can be achieved when perceived opportunities (challenges) are in balance with the action capabilities (skills) of an experience (Csikszentmihalyi, 1975, 1990). This concept has been extended in virtual environments with "Gameflow," where user enjoyment is a result of balancing an environment's required concentration, challenge, skill, control, goals, feedback, immersion, and interaction of an environment (Sweetser and Wyeth, 2005). Similarly to the Yerkes-Dodson Law, augmenting the ultimate display for physical rehabilitation enables a controlled

environment to develop and measure optimal models of user engagement with therapy tasks.

5.3. Limitations of This Review

There are many limitations to consider in this review. Firstly, the fields of rehabilitation, immersive media, and biofeedback are vast and ever-changing. However, we believe this review provides an adequate snapshot of the current potential that each of these literature review themes holds for assistive application. Additionally, this study primarily focused on iVR through head-mounted displays. Other extended reality mediums, such as spatial computing with augmented and mixed reality headsets, should be considered. With the advent of 5G edge computing and many extended reality devices exploring high-throughput streaming and social interaction, new paradigms for iVR-based therapy may emerge in the coming years. Yet, we believe that this review of iVR-based HMDs is still very relevant due to newfound consumer adoption and the necessity to drive and review the limitations of a field that is currently still maturing.

6. CONCLUSION

Immersive virtual reality paired with multi-modal stimuli and biofeedback for healthcare is an emerging field that is underexplored. Our bridging review of iVR contributes to the body of knowledge toward understanding immersive assistive technologies by reviewing the feasibility of a biometric-infused immersive media approach. We reviewed and discussed iVR therapy applications, the behavioral theory behind iVR, and quantification methods using biofeedback. Common limitations in all these fields include the need to develop a standard database for iVR-affective stimuli and the need for transparent dissemination of experimental methodology, tools, and user demographics in evaluating iVR for healthcare. We proposed an ultimate display augmented for rehabilitation that utilizes virtual reality by combining immersive media, biofeedback, and wearable robotics. Specific outcomes of such a system may include new algorithms and tools to integrate emotion feedback in iVR for researchers and therapists, discoveries of new relationships between emotion and action in physical therapy, and new methodologies to produce optimal therapy benefits for patients by incorporating immersive media and biometric feedback. These results may lead to deeper mediums for both clinical and at-home therapy. They may uncover novel approaches to rehabilitation and increase the affordability, accuracy, and accessibility of treatment. We believe that future of iVR healthcare may become a new field of therapy; a field that is centered on immersive physio-rehab that reacts, learns, and adapts its stimuli and difficulty to each individual user to establish a more engaging and impactful rehabilitation experience.

AUTHOR CONTRIBUTIONS

AE wrote the first draft of the manuscript. SK assisted with the literature review search and provided further writing. AE iteratively revised the manuscript with SK. The ideas of the paper were formulated through a 4-year collaboration with local physical therapy centers in Santa Cruz, California, to which all authors contributed. All authors contributed to the article and approved the submitted version.

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REVIEW
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The Untapped Potential of Virtual Reality in Rehabilitation of Balance and Gait in Neurological Disorders

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Dynamic systems theory transformed our understanding of motor control by recognizing the continual interaction between the organism and the environment. Movement could no longer be visualized simply as a response to a pattern of stimuli or as a demonstration of prior intent; movement is context dependent and is continuously reshaped by the ongoing dynamics of the world around us. Virtual reality is one methodological variable that allows us to control and manipulate that environmental context. A large body of literature exists to support the impact of visual flow, visual conditions, and visual perception on the planning and execution of movement. In rehabilitative practice, however, this technology has been employed mostly as a tool for motivation and enjoyment of physical exercise. The opportunity to modulate motor behavior through the parameters of the virtual world is often ignored in practice. In this article we present the results of experiments from our laboratories and from others demonstrating that presenting particular characteristics of the virtual world through different sensory modalities will modify balance and locomotor behavior. We will discuss how movement in the virtual world opens a window into the motor planning processes and informs us about the relative weighting of visual and somatosensory signals. Finally, we discuss how these findings should influence future treatment design.

Keywords: posture, locomotion, sensorimotor, avatar, intervention

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INTRODUCTION

Virtual reality (VR) is a compelling and motivating tool that can be used to modulate neural behavior for rehabilitation purposes. Virtual environments can be developed as simple two-dimensional visual experiences and as more complex three-dimensional gaming and functional environments that can be integrated with haptics, electromyography, electroencephalography, and fMRI. These environments can then be used to address a vital need for rehabilitative training strategies that improve functional abilities and real-world interaction. There has been a concerted effort to determine whether motor learning in VR transfers to the physical world (Levac et al., 2019). Although this is important for determining measurable goals for intervention with VR, the sole focus on diminishing a motor deficit without controlling the perceptual factors within the virtual environment could actually interfere with task transfer and the rehabilitation process. Mounting evidence suggests that VR contributes to the complex integration of information from multiple sensory pathways and incorporates the executive processing needed to perceive this multimodal information (Keshner and Fung, 2019). Thus, VR is a rehabilitation tool that can be designed to address the perception-action system required for motor planning, a vital part of motor learning and performance, as well as motor execution.

In humans, common neural activation during action observation and execution has been well documented. A variety of functional neuroimaging studies, using fMRI, positron emission tomography, and magnetoencephalography, have demonstrated that a motor resonance mechanism in the premotor and posterior parietal cortices occurs when participants observe or produce goal directed actions (Grèzes et al., 2003; Hamzei et al., 2003; Ernst and Bülthoff, 2004). Mirror neurons in the ventral premotor and parietal cortices of the macaque monkey that fire both when it carries out a goal-directed action and when it observes the same action performed by another individual also provides neurophysiological evidence for a direct matching between action perception and action production (Rizzolatti and Craighero, 2004).

The concept of perception-action coupling has been accepted since Gibson (Gibson, 1979) who argued that when a performer moves relative to the environment, a pattern of optical flow is generated that can then be used to regulate the forces applied to control successive movements (Warren, 1990). In other words, we organize the parameters of our movement in relation to our perception of the signals we are receiving from the environment, and the change resulting from our action will then change the environment we must perceive for any subsequent action. Thus, how we perceive the environmental information will always affect how we organize and execute an action. Not taking into account the environmental factors that influence perception during training may well confound any assessments of performance and transfer of training (Gorman et al., 2013).

The essence of VR is the creation of the environment. Environments are created for many purposes ranging from industrial to entertainment and gaming to medical (Rizzo and Kim, 2005; Levin et al., 2015; Garrett et al., 2018; Keshner et al., 2019). Environments have been developed to overlay virtual objects on the physical world (i.e., augmented reality) or to present a fully artificial digital environment (i.e., VR). Rarely, however, is the motor ability of the performer considered in the design of these environments. In this study we will present work from our laboratories in which we specifically focused on coupling of the environmental and motion parameters.

MANIPULATING VISUAL MOTION INFORMATION (OPTIC FLOW)

In a seminal paper initially published in 1958, Gibson formulated the foundations of what would become an influential theory on the visual control of locomotion (Gibson, 2009). Among key aspects of this theory was the role visual kinaesthesis, or optic flow, in the perception of egomotion and control of locomotion (Warren, 2009). Since early 2000, VR technology has undoubtedly contributed to our understanding of the role of optic flow and other sources of visual information in the control of human posture and locomotion (Warren et al., 2001; Wilkie and Wann, 2003).

Several psychophysical phenomena are attributed to the impact of optic flow on perception. Presence and immersion describe the user's belief in the reality of the environment (Slater, 2003). These terms have been used interchangeably, but they should be distinguished from the perspective of the measurement tool. According to Slater (Slater, 2003), immersion is a measure of the objective level of sensory fidelity provided by a VR system; presence is a measure of the subjective psychological response of a user experiencing that VR system.

Vection is the sensation of body motion in space produced purely by visual stimulation. This illusory motion of the whole body or of body parts is induced in stationary observers viewing environmental motion (Dichgans and Brandt, 1972; Dichgans et al., 1972; Palmisano et al., 2015). Examples of such a conflict occur in daily life when watching a moving train and sensing that it is the train and not yourself who is moving (Burr and Thompson, 2011). It is generally agreed that this illusion of self-motion results from a sensory conflict or mismatch that cannot be resolved by the CNS. Vection has also been defined more broadly as the conscious subjective experience of self-motion (Ash et al., 2013) that is crucial for successful navigation and the prevention of disorientation in the real world (Riecke et al., 2012).

Lastly, perception of self-motion is a challenging problem in the interpretation of multiple sensory inputs, requiring the neural combination of visual signals (e.g., optic flow), vestibular signals regarding head motion, and also somatosensory and proprioceptive cues (Deangelis and Angelaki, 2012). To perform successfully, we need to link sensory information to the context of the movement and determine whether there is a match between the visual motion and our vestibular and somatosensory afference and then shape our movement to accurately match the demands of the environment (Hedges et al., 2011). Consistent multisensory information about self-motion, rather than visual-only information, has been shown to reduce vection and improve both heading judgment and steering accuracy (Telford et al., 1995). Subjects demonstrated no compensation for self-motion that was defined solely by vestibular cues, partial compensation (47%) for visually defined self-motion, and significantly greater compensation (58%) during combined visual and vestibular self-motion (Dokka et al., 2015). Body posture will orient to a visual, somatosensory, or vestibular reference frame depending on the task, behavioral goals, and individual preference (Streepey et al., 2007b; Lambrey and Berthoz, 2007). Development across the lifespan and damage to the CNS may produce a shift in sensory preferences and thereby alter the responsiveness to any of the sensory pathways resulting in altered motor behavior (Slaboda et al., 2009; Yu et al., 2020). Thus, understanding how virtual environment parameters influence motor planning and execution is essential if we are to use virtual reality effectively for training and intervention.

Evidence From VR-Based Neuroimaging Studies

Through the combination of VR and neuroimaging tools, key brain regions involved in the perception and use of optic flow during simulated "locomotor tasks" were unveiled. Human motion area hMT+ and ventral intraparietal cortex (VIP) play a role in the perception of egomotion from optic flow (Morrone et al., 2000; Dukelow et al., 2001; Wall and Smith, 2008), while a region of the intraparietal sulcus (IPS) would be responsible for identifying heading from optic flow information (Peuskens et al., 2001; Liu et al., 2013). PET and MRI studies indicate that when both retinal and vestibular inputs are processed, there are changes in the medial parieto-occipital visual area and parietoinsular vestibular cortex (Brandt et al., 1998; Dieterich and Brandt, 2000; Brandt et al., 2002), as well as cerebellar nodulus (Xerri et al., 1988; Kleinschmidt et al., 2002), suggesting a deactivation of the structures processing object-motion when there is a perception of physical motion. When performing VR-based steering tasks, additional regions such as the premotor cortex and posterior cerebellum get recruited (Field et al., 2007; Billington et al., 2010; Liu et al., 2013). The latter two brain regions would contribute to the planning and online monitoring of observer's perceived position in space, while also contributing to the generation of appropriate motor responses (Field et al., 2007; Liu et al., 2013). Interestingly, a study which combined EEG to a VR setup during Lokomat-supported locomotion also showed an enhancement in premotor cortex activation when performing a steering task in first or third person view compared to conditions where no locomotor adaptations were required, which the authors also attributed to an enhanced need for motor planning (Wagner et al., 2014).

In most recent VR-based neuroimaging studies, individuals are immersed in more realistic environments and perform tasks of increasing complexity such as attending to or avoiding moving objects during simulated self-motion, where both perceived self-motion and object motion are at play (Calabro and Vaina, 2012; Huang et al., 2015; Pitzalis et al., 2020). Collectively, the fundamental knowledge acquired through VR-based neuroimaging experiments is key as it has allowed rehabilitation scientists to pose hypotheses and explain impaired locomotor behaviors and the heterogeneity of thereof in clinical populations with brain disorders such as stroke or Parkinson's disease. Existing VR-based neuroimaging studies, however, remain foremost limited by their lack of integration of actual locomotor movements and nonvisual self-motion cues (Chaplin and Margrie, 2020). Multisensory convergence takes place at multiple levels within the brain. As an example, animal research has shown that MSTd and the parietoinsular vestibular contribute to a coherent percept of heading by responding both to vestibular cues and optic flow (Duffy, 1998; Angelaki et al., 2011)—an observation that was made possible by exposing the animal to a combination of optic flow manipulation and actual body translation in space. In human research, the emergence of mobile neuroimaging tools (e.g., fNIRS, EEG) and more robust analysis algorithms now makes it possible to examine the neural substrates of actual locomotion (Gramann et al., 2011; Brantley et al., 2018; Gennaro and De Bruin, 2018; Nordin et al., 2019; Wagner et al., 2019). Studies combining VR as well as other technologies (e.g., motion platform, robotic devices) to mobile neuroimaging can be expected, in the near future, to flourish and advance our understanding of locomotor control in complex, comprehensive yet controlled multisensory environments.

What Have We Learned From Lab-Based Postural Control Studies

Our studies in immersive VR environments (using both projection and head mounted display (HMD) technology) reveal that it is nearly impossible for a performer to ignore the dynamic visual stimulus (Keshner and Kenyon, 2000, 2009; Cleworth et al., 2012). As shown in a seminal paper by Dichgans et al. (1972), sensitivity to a virtual visual stimulus is greatly increased when there is a combination of meaningful inputs (Dichgans et al., 1972). Measures of head, trunk, and lower limb excursions revealed that the majority of participants compensated in the opposite direction but at the same frequency for motion of a translating platform in the dark (Keshner et al., 2004). When on a stationary platform with a translating visual scene, participants matched the frequency and direction of the scene motion with their head and trunk but at much smaller amplitudes. Combining platform and visual scene motion produced the greatest amplitudes of motion occurred in all body segments. Additionally, frequency content of that movement reflected both the frequencies of the platform and the visual scene suggesting that the sense of presence was greatly intensified when producing self-motion within a dynamic visual environment (**Figure 1**).

These results suggest that the postural response was modulated by all of the available sensory signals. In fact, the data strongly establish that kinematic variables of postural behavior are responsive to the metrics of the multimodal inputs. In particular, postural behavior has been shown to be influenced by the velocity, direction, and frequency parameters of the optic flow (**Figure 2**). For example, healthy young adults standing on a tilting platform in a 3-wall projection environment (Dokka et al., 2010; Wang et al., 2010) modified the direction, velocity, and amplitude of their COM motion in relation to the velocity of a visual scene rotating in the pitch direction. When standing on a stable surface, healthy young adults matched the direction of their head and trunk swaying to the direction of visual motion in both pitch and roll.

Although velocity and direction may be governed by optic flow, magnitude of the response does vary across individuals (Keshner et al., 2004; Streepey et al., 2007a; Dokka et al., 2009). Healthy young adults in front of a wide field of view virtual scene that translated in the anterior-posterior (a-p) direction stood upon a rod that supported 100% or 45% of their foot length; thus, the base of support was whole or narrowed. Even in these healthy, young adults, success at maintaining a vertical orientation was compromised when standing on the narrowed base of support; however, the sway of about half the participants matched the frequency of the visual scene whereas the other half did not demonstrate a predominant frequency. This suggests a

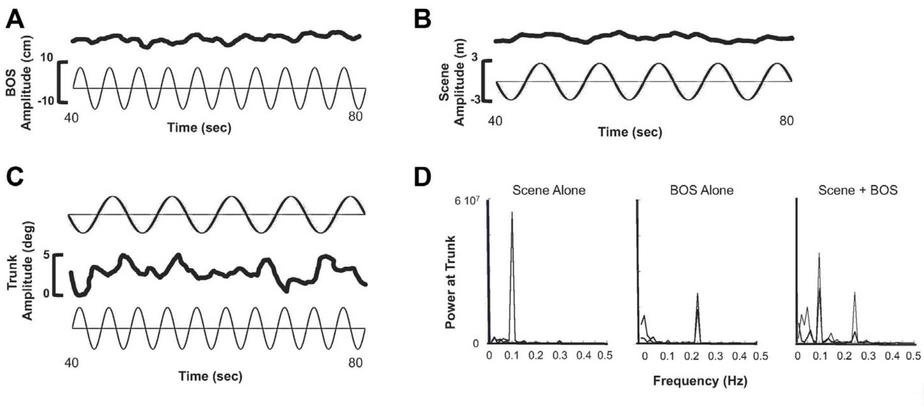

FIGURE 1 | (A) Trunk excursion (top trace) to sinusoidal a-p translation (bottom trace) of the base of support (BOS) at 0.25 Hz. **(B)** Trunk excursion (top trace) to sinusoidal a-p optic flow (scene) at 0.1 Hz. **(C)** Trunk excursion (middle trace) when 0.25 Hz motion of the BOS (bottom trace) and 0.1 Hz of the scene (top trace) occur simultaneously. **(D)** FFT analysis demonstrating power at the trunk reflects frequency of the stimulus, i.e., the scene **(left)**, the BOS **(middle)**, and simultaneous BOS and scene motion **(right)**.

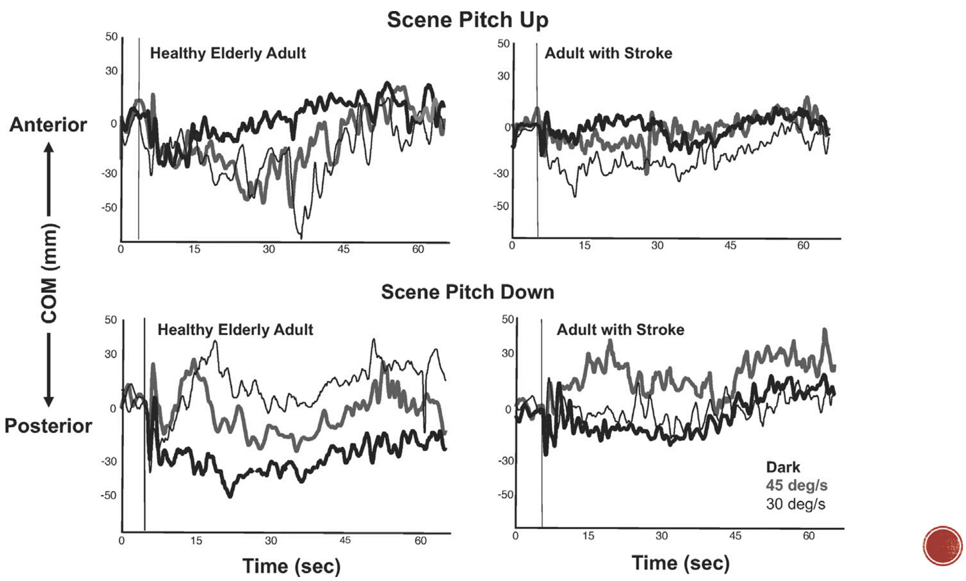

FIGURE 2 | Center of mass (COM) excursions during a-p translations of a platform at 0.25 Hz while standing in the dark (bold black line) and while viewing continuous pitch rotations of optic flow at 30 deg/sec (thin black line) and 45 deg/sec (bold gray line). ***Top graphs:*** responses to pitch-up rotations of the scene in a healthy 62-year-old adult **(left)** and 65 year-old-adult with right hemiplegia **(right)**. ***Bottom graphs:*** responses to pitch down rotations of the scene in a healthy elderly adult **(left)** and elderly adult with stroke **(right)**. Vertical thin line indicates start of optic flow field.

preferential sensory referencing in some participants to the sinusoidal visual signals and in others to the proprioceptive signals from the body. Intraindividual variability and task dependency that is demonstrated in the virtual environment (Keshner and Kenyon, 2000; Streepey et al., 2007b) imply that postural control is both task and organism dependent and should not be treated as a stereotypical, automatic behavior.

A developmental impact on the ability to process optic flow was revealed during a functional sit-to-stand task (Slaboda et al., 2009). Healthy children (8–12 years) and adults (21–49 years) were seated in a virtual environment that rotated in the pitch and roll directions. Participants were told to stand either (1) concurrent with onset of visual motion or (2) after an immersion period in the moving visual environment and (3) without visual input. Both adults and children reduced head and trunk angular velocity after immersion in the moving visual environment. Unlike adults, children demonstrated significant differences in displacement of the head center of mass during the immersion and concurrent trials when compared to trials without visual input. These data support previous reports (Keshner and

Kenyon, 2000; Keshner et al., 2004) of a time-dependent effect of vision on response kinematics in adults. Responses in children are more influenced by the initial presence or absence of vision from which we might infer poorer error correction in the course of an action.

Utilizing Optic Flow for Postural Rehabilitation

Optic flow in the virtual environment robustly influences the organization of postural kinematics. This influence, however, fluctuates with the integrity of the CNS and the perceptual experiences of each individual. Sensory signals are often reweighted in individuals as they age and with neurological disability, which then alters the postural response to optic flow (Slaboda et al., 2009; Yu et al., 2018). Thus, the success of any therapeutic intervention employing VR needs to consider the parameters of visual motion of the virtual environment. There are, however, some global precepts that can guide the deployment of any VR intervention. Specifically, studies have consistently demonstrated that (1) the direction of full-field optic flow will regulate the direction of postural sway (Keshner and Kenyon, 2009); (2) increasing velocity will increase the magnitude of postural sway (Dokka et al., 2009; Wang et al., 2010); (3) multiple sensory frequencies will be reflected in the body segment response frequencies (Keshner et al., 2004; Slaboda et al., 2011a); and (4) the influence of optic flow becomes more substantial during self-motion (Dokka et al., 2010).

Training individuals that have instability and sensory avoidance to produce effective postural behaviors have obvious value and there are some studies demonstrating carryover to the functional postural behavior of individuals with labyrinthine loss (Haran and Keshner, 2008; Bao et al., 2019), Parkinson's disease (Bryant et al., 2016; Nero et al., 2019; Rennie et al., 2020), and stroke (Van Nes et al., 2006; Madhavan et al., 2019; Saunders et al., 2020). The very strong directional effect of optic flow on posture and spatial orientation (Keshner and Kenyon, 2000) would support incorporating this technology into any balance rehabilitation program.

The ability to change response magnitudes relative to visual velocity has been demonstrated in young healthy adults and in individuals diagnosed with dizziness (Keshner et al., 2007), stroke (Slaboda and Keshner, 2012), and cerebral palsy (Yu et al., 2018; Yu et al., 2020) when support surface tilts were combined with sudden rotations of the visual field. Both of these variables are time dependent and require further clinical trials to determine appropriate dosage of these interventions. Sensory reweighting, however, has been shown to be frequency dependent and requires control of multimodal stimuli. Angular displacements of the head, trunk, and head with respect to the trunk consistently revealed that healthy individuals linked their response parameters to visual inputs and those with visual sensitivity as measured with a Rod and Frame test could not use the visual information to appropriately modulate their responses. Instead, individuals with visual dependence, with or without a history of labyrinthine dysfunction, tended to produce longer duration and larger magnitude angular velocities of the head than healthy individuals in all planes of motion and at all scene velocities (Keshner and Dhaher, 2008; Wright et al., 2013).

These findings could be explained by an inability to adapt the system to the altered gains resulting from the neurological damage so that they could not accommodate to sensory signals with which they had no prior experience (i.e., constant motion of the visual world). A similar outcome was observed in healthy young adults who received vibrotactile noise on the plantar surface of the foot during quiet stance. Stochastic resonant vibration of the lower limbs in older adults and patients with stroke has been shown to reduce postural instability (Van Nes et al., 2004; Guo et al., 2015; Lu et al., 2015; Leplaideur et al., 2016). Although vibration does not shorten the time to react to instability, it can decrease the amplitude of fluctuation between the controlled body segment and unstable surface thereby increasing the likelihood that a corrective response will be effective. While viewing visual field rotations, however, magnitude and noise of their center of mass (COM) and center of pressure (COP) responses increased rather than decreased with vibration (Keshner et al., 2011) suggesting that, by increasing noise in the system, individuals were unable to fully compensate for the disturbances. The use of noise and sensory mismatch to encourage desensitization or compensation is currently being explored for the treatment of dizziness and postural instability (Pavlou et al., 2011; Pavlou et al., 2012; Sienko et al., 2017; Bao et al., 2019). Individuals with dizziness from concussion or labyrinthine dysfunction have also been exposed to erroneous or conflicting visual cues (visual-vestibular mismatch) while attempting to maintain balance (Bronstein and Pavlou, 2013; Pavlou et al., 2013). Results suggest that exposure to unpredictable and noisy environments can be a valuable tool for motor rehabilitation. Dosages (e.g., timeframe and range of stimulation) of the intervention need to be further explored with controlled trials.

What Have We Learned From Lab-Based Locomotor Studies

An extensive body of literature has examined the role of visual self-motion in the control of locomotion by selectively manipulating the direction or speed of the optic flow provided through the virtual environment. Our work and that of others have shown that one's walking speed is affected by changing optic flow speeds and show an out-of-phase modulation pattern. In other words, slower walking speeds are adopted at faster optic flow speeds while faster walking speeds are observed at slower optic flows (Pailhous et al., 1990; Konczak, 1994; Prokop et al., 1997; Varraine et al., 2002). Such strategy would allow reducing the incongruity that arises from the mismatch between proprioceptive information from the legs and the visual flow presented in the virtual simulation (Prokop et al., 1997; Lamontagne et al., 2007). The presence of optic flow during treadmill walking also influences one's ability to correct small stepping fluctuations (Salinas et al., 2017). Compelling evidence also support the role of optic flow in the control of locomotor steering (Jahn et al., 2001; Warren et al., 2001; Mulavara et al., 2005; Turano et al., 2005; Bruggeman et al., 2007). In the latter body of literature, a shift in the focus of expansion of the optic flow is externally induced and this causes the participants to perceive a shift in their heading direction. As a result, the participants correct the perceived shift by altering their walking trajectory in the opposite direction. Our team has also shown that depending on whether the shift in the focus of expansion is induced through rotational vs. translational flow, different steering strategies emerge (Sarre et al., 2008). In the former scenario, a steering strategy characterized by head, trunk, and foot reorientation is observed, while the latter scenario rather induces a typical "crab walk pattern" characterized by a change of walking trajectory with very little body segment reorientation. Such crab walking pattern has also been reported in other VR studies that used translational optic flow (Warren et al., 2001; Berard et al., 2009).

Interestingly, if the same rotational optic flow is generated via a simulated head yaw rotation (camera rotation in VR) vs. an actual head rotation, a different locomotor behavior also emerges, whereby the simulated but not the actual head rotation results in a trajectory deviation (Hanna et al., 2017). Such findings support the potential contribution of the motor command (here neck and oculomotor muscles) in heading estimation (Banks et al., 1996; Crowell et al., 1998). These findings also corroborate the presence of multisensory integration of both visual and nonvisual information (e.g., vestibular, proprioceptive, and somatosensory) to generate a single representation of self-motion and orientation in space (De Winkel et al., 2015; Acerbi et al., 2018).

Influences of Optic Flow on Locomotor Rehabilitation

Collectively, the above-mentioned observations demonstrate that while locomotor adaptions rely on multisensory integration, vision and here, more specifically, optic flow exert a powerful influence on the observed behavior. Findings presented also provide concrete examples as to how optic flow information can be selectively manipulated to alter locomotor behavior. Thus, not only is the replication of reality in VR not a necessity, but the selective manipulation of the sensory environment can and should as needed be capitalized on to promote the desired outcome. To allow for such manipulations to be effective in a given clinical population, however, the latter must show a residual capacity to perceive and utilize optic flow information while walking.

The perception of optic flow and its use in locomotion have been examined in several clinical populations such as older adults (Chou et al., 2009; Lalonde-Parsi and Lamontagne, 2015) and Parkinson's disease patients (Schubert et al., 2005; Davidsdottir et al., 2008; Young et al., 2010; Van Der Hoorn et al., 2012), but let us use stroke as an example to demonstrate applications in rehabilitation. Following stroke, the perception of optic flow often is preserved (Vaina et al., 2010; Ogourtsova et al., 2018) but becomes affected when the lesion is located in rostrodorsal parietal and occipitoparietal areas of the brain, which are involved in global motion perception (Vaina et al., 2010). In presence of unilateral spatial neglect (USN), the bilateral perception of optic flow (e.g., optic flow direction and coherence) becomes dramatically altered (Ogourtsova et al., 2018). In fact, altered optic flow perception along with USN severity as measured by clinical tests explain 58% of the variance in locomotor heading errors in individuals with poststroke USN (Ogourtsova et al., 2018). Such observations emphasize the need to consider the role of visual-perceptual disorders in poststroke locomotor impairments.

Beyond studies examining the perception of optic flow perception, our group has also examined the use of optic flow during locomotion by manipulating the direction or speed of the virtual environment (Lamontagne et al., 2007; Lamontagne et al., 2010; Berard et al., 2012; Aburub and Lamontagne, 2013). From these experiments emerged three main observations: (1) globally, the ability to utilize OF information during walking is altered following stroke; (2) there is however a large heterogeneity across individuals, ranging from no alterations to profound alterations in locomotor responses to optic flow manipulations; and (3) most individuals show some degree of modulation (albeit incomplete or imperfect) of their locomotor behavior in response to optic flow manipulation. Thus, one can infer that there is potential to induce the desired locomotor adaptations through optic flow manipulation in stroke survivors. However, integration of such manipulations in intervention studies for locomotor rehabilitation is scare and evidence of effectiveness is lacking.

In 2012, Khang and collaborators combined treadmill training to optic flow speed manipulation for 4 weeks and examined the effects on balance and locomotion following stroke (Kang et al., 2012). Unfortunately, although the study showed larger posttraining gains in walking speed and endurance in the optic flow manipulation group vs. control groups receiving either conventional treadmill training or a stretching program, the study design did not allow to dissociate the contribution of VR itself from that of the optic flow manipulation. Furthermore, it is unclear if any online walking speed adaptation took place during training given the absence of a self-pace mode on the treadmill. A study from Bastian's lab also showed that combining split-belt walking to an incongruent optic flow that predicted the belt speed of the next step enhanced the rate of learning during split-belt locomotor adaptations in healthy individuals (Finley et al., 2014). To date, however, the integration of such paradigm as part of an intervention to enhance poststroke gait asymmetry remains to be examined.

INTERACTION WITH AVATARS

In recent years, and thanks to technological development that allows tracking and displaying body movements in real-time in a virtual environment, the development of avatar-based paradigms in rehabilitation has emerged. Unlike virtual humans or agents which are controlled by computer algorithms, avatars are controlled by the users and "mimic" their movements in real-time. The avatar can represent either selected body parts (e.g., arms or legs) or the full body. They can also be viewed from a first-person perspective (1 PP) or third-person perspective (3 PP). In the paragraphs below, we are mainly concerned with exploring the impact of avatar-based feedback as a paradigm to enhance postural control and locomotion in clinical populations, but literature on upper extremity research that explores mechanisms is also examined.

Why Avatar-Based Feedback

Potential principles of action of avatar-based feedback are multiple and, as stated in a recent expert review on virtual reality, they open a "plethora of possibilities for rehabilitation" (Tieri et al., 2018). When exposed to virtual simulations representing body parts or the full body, a phenomenon referred to as virtual embodiment can develop. This sense of embodiment translates as the observer experiencing a sense of owning the virtual body simulation (ownership) and of being responsible for its movement (agency) (Longo et al., 2008; Pavone et al., 2016). While such sense of embodiment is subjectively reported as higher for 1 PP vs. 3 PP (Slater et al., 2010; Petkova et al., 2011; Pavone et al., 2016), we argue that the latter perspective remains very useful for postural and locomotor rehabilitation (as one does not necessarily look down at their feet, for instance, when standing or walking). The similarity between the virtual vs. real body part(s) (Tieri et al., 2017; Kim et al., 2020; Pyasik et al., 2020), the real-time attribute or synchrony of the simulation with actual movements (Slater et al., 2009; Kim et al., 2020), and the combination of sensory modalities (e.g., visuotactile (Slater et al., 2008) or visuovestibular (Lopez et al., 2008; Lopez et al., 2012)) are factors that enhance the illusory sensation.

Neuroimaging experiments indicate that the premotor areas (pre-SMA and BA6) are involved in the sense of agency (Tsakiris et al., 2010), while ownership would be mediated through multimodal integration that involves multiple brain areas including the somatosensory cortex, intraparietal cortex, and the ventral portion of the premotor cortex (Blanke, 2012; Guterstam et al., 2019; Serino, 2019). Mirror neurons located in the ventral premotor cortex and parietal areas, but also in other regions such as visual cortex, cerebellum, and regions of the limbic system, also fire when an individual observes someone else's action (Molenberghs et al., 2012) and are likely activated when exposed to avatar-based feedback. Passively observing modified (erroneous) avatar-based feedback also leads to activation of brain regions associated with error monitoring (Pavone et al., 2016; Spinelli et al., 2018), which is a process essential for motor learning.

During actual locomotion, the performance of a steering task while exposed to avatar feedback provided in 1 PP or 3 PP was shown to induce larger activation in premotor and parietal areas compared to movement-unrelated feedback or mirror feedback (Wagner et al., 2014). While such enhanced activation appears primarily caused by the motor planning and visuomotor demands associated with gait adaptations (Wagner et al., 2014), it may as well have been potentiated by a sense of embodiment and/or mirror neuron activations. More recently, another study reported an event-related synchronization in central-frontal (likely SMA) and parietal areas both during actual and imagined walking while exposed to 1 PP avatar-based feedback (Alchalabi et al., 2019). This event-related synchronization was attributed by the authors to the high sense of agency experienced during these conditions. Together, the latter two locomotor studies provide preliminary evidence that the body of knowledge on avatar-based feedback gathered primarily via upper extremity experiments can be extended, at least in part, to locomotion. Most importantly, observations from neuroimaging experiments as a whole indicate that avatar-based feedback does modulate brain activation. Through repeated exposure, such a paradigm could thus support neuronal reorganization and recovery following a neurological insult.

From a more pragmatic perspective, avatar-based feedback also capitalizes on the remarkable ability of the human brain to perceive and interpret biological motion information (Johansson, 1973). This remarkable ability allows recognizing features such as the nature of the activity being performed (e.g., walking), gender and emotion, even when exposed to impoverished visual simulations such as point-light displays (Johansson, 1973; Troje, 2002; Atkinson et al., 2004; Schouten et al., 2010). For similar reasons, we as human can easily identify even the most subtle limp when observing a walking pattern, which makes avatar-based feedback a potentially powerful approach to give and receive feedback on complex tasks such as locomotion. Avatar feedback further allows providing real-time feedback on the quality of movement (knowledge of performance) (Liu et al., 2020b), which is especially challenging for clinicians to do. In line with previous literature on embodiment presented earlier, avatar-based feedback may also impact recovery by enhancing movement awareness, which is affected in clinical populations such as stroke (Wutzke et al., 2013; Wutzke et al., 2015).

Manipulation of Avatar-Based Feedback

Avatar-based feedback can be manipulated in different ways (e.g., view, available sensory modality, modified vs. unmodified feedback, etc.), yet the optimal parameters to obtain the desired responses remain unclear. In a recent study from our laboratory, we posed the question "which avatar view between the front, back and side view, yields the best instantaneous improvement in poststroke gait asymmetry?" (Liu et al., 2020b). Participants were tested while exposed to 3 PP full-body avatars presented either in the front, back, or paretic side view and resulting changes in gait symmetry were examined. The side view, which likely provides the best perspective on the temporal-distance parameters of gait, was the only view that induced enhanced spatial symmetry but only in those participants who initially presented a larger step on the paretic side. This finding was caused by the participants increasing their step length on the nonparetic side when exposed to the avatar, which resulted in improved symmetry only in those with a large paretic step. Such an observation suggests that the initial profile of the participant matters and, by extension, that avatar-based feedback may not be suitable for all individuals. Of note, manipulating 3 PP viewing angle of a virtual arm was also found to alter kinematic outcomes during a reaching task performed while standing (Ustinova et al., 2010). Avatar view thus emerges as a factor to consider in the design of an intervention.

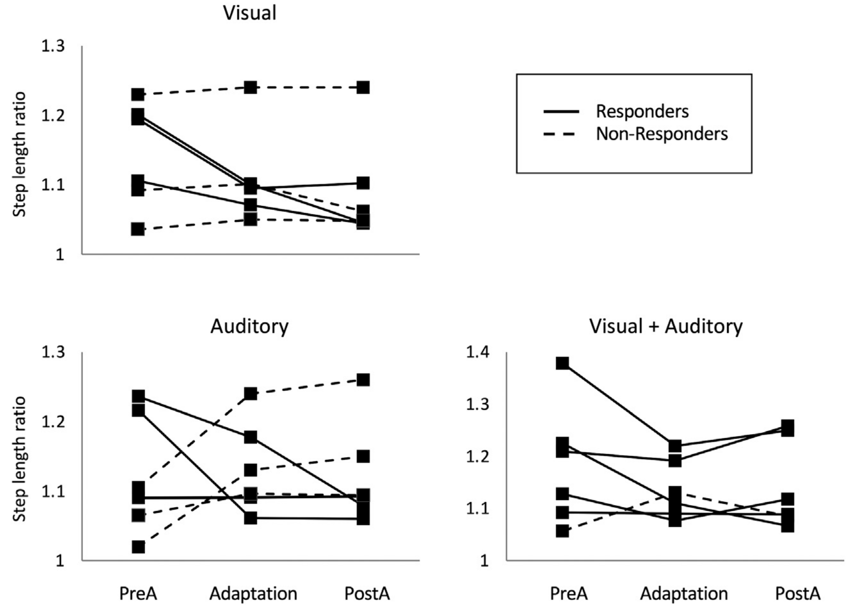

FIGURE 3 | Step length ratio values exhibited by stroke survivors walking on a self-paced treadmill while exposed to avatar-based feedback in the visual, auditory, and combined (visual + auditory) sensory modality. Values are presented for the preadaptation (no avatar for 30 s), adaptation (avatar present for 1 min), and postadaptation periods (avatar removed for 1 min). Responders, that is individuals showing a reduction of their step length ratio during the adaptation period, are represented by a plain line, while non-responders are represented by a dotted line. Note the larger number of responders to the combined vs. individual sensory modalities.

In a second series of experiments, we examined the impact of modulating the sensory modality of avatar-based feedback on poststroke gait asymmetry. The feedback consisted either of a 3 PP visual avatar in the side view (visual), footstep sounds (auditory), or a combination of visual avatar and footstep sounds (combined modality) (Liu et al., 2020a). Although these results are preliminary, there is a clear implication that combining sensory modalities yielded the largest improvements in spatial symmetry (**Figure 3**). These results are in agreement with prior studies on other types of multimodal simulation, such as the combination of a visual avatar to tactile or haptic feedback, that were found to have additional beneficial effects on the performance of healthy individuals performing a stepping task (Koritnik et al., 2010) and on the ability of individuals with spinal cord injury to integrate virtual legs to their body representation (Shokur et al., 2016).

The evidence supports the use of multimodal feedback to modulate or train functional locomotion from a rehabilitation perspective. In upper extremity rehabilitation research, a well-studied approach consists of artificially increasing the perceived performance error through visual or haptic feedback (i.e., error augmentation paradigm) (Israely and Carmeli, 2016; Liu et al., 2018). Similarly, manipulating avatar-based feedback offers an opportunity to modify the locomotor behavior. In 2013, Kannape and Blanke manipulated the temporal delay of avatar-based feedback and found that, while gait agency decreased with longer delays, participants "systematically modulated their stride time as a function of the temporal delay of the visual feedback", making faster steps in presence of incongruous temporal feedback (Kannape and Blanke, 2013). More recently, a preliminary study examined the impact of stride length manipulation through hip angle modifications and found a clear trend toward larger step lengths when exposed to larger avatar step lengths (Willaert et al., 2020). Such experiments provide preliminary evidence that modified avatar-based feedback can lead to locomotor adaptations either in the temporal or spatial domain. Avatar-based feedback can further be augmented with visual biofeedback on specific kinematic or kinetic features of the gait cycle. In children with cerebral palsy, for instance, avatar-based feedback was augmented with biofeedback on knee or hip excursion, as well as step length, resulting in further improvements in those parameters compared to avatar-based feedback alone (Booth et al., 2019).

Collectively, findings in this section demonstrate that avatar-based feedback can be effectively manipulated to modify locomotor behavior and target specific features of gait. It can also be used as a mean to enhance the control of movement through brain computer interface (Wang et al., 2012; King et al., 2013; Nierula et al., 2019). Further research is needed, however, to understand how it can be optimized to promote the desired outcome. At this point in time, intervention studies that specifically focus on repeated exposure to avatar-based feedback as an intervention for postural or locomotor rehabilitation in populations with sensorimotor disorders are crucially lacking.

INTERACTION WITH VIRTUAL HUMANS

External Cuing

Inclusion of external agents (i.e., virtual humans) in virtual scenarios has emerged as a means to modulate locomotion in the context of rehabilitation. Such an approach stems in part from a large body on research on the use of external sensory cueing (e.g., visual or auditory) to modulate the temporal-distance factors of gait both in healthy individuals (Rhea et al., 2014; Terrier, 2016) and individuals with gait disorders (Roerdink et al., 2007; Spaulding et al., 2013). It also stems from the fact that when two individuals walk together (i.e., when exposed to biological sensory cues), the locomotor behavior is modulated as a result of a mutual interaction between the two walkers (Ducourant et al., 2005) and a phenomenon of "gait synchronization", whereby a follower matches the gait pattern of the leader, can be observed (Zivotofsky and Hausdorff, 2007; Zivotofsky et al., 2012; Marmelat et al., 2014; Rio et al., 2014). Such gait synchronization can be fostered through different sensory channels (e.g., visual, tactile, and auditory) and is enhanced with multimodal simulations (Zivotofsky et al., 2012). In postural tasks, a similar phenomenon of synchronization of postural sway is observed when individuals are standing and having a physical contact (Reynolds and Osler, 2014), while looking at each other (Okazaki et al., 2015) or while sharing a cooperative verbal task (Shockley et al., 2003). Given the flexibility and control afforded by VR, virtual humans can also be used to "cue" and modulate behavior, as demonstrated through different studies which have examined instantaneous effects on locomotion (Meerhoff et al., 2017; Meerhoff et al., 2019; Koilias et al., 2020). While promising as a tool for rehabilitation, however, evidence of effectiveness of external cueing through virtual humans as an intervention either for posture or locomotion remains to be established.

Pedestrian Interactions

Virtual humans can also be used for the assessment and training of complex locomotor tasks such as avoiding collisions with other pedestrians, which is a task essential for independent community walking (Patla and Shumway-Cook, 1999; Shumway-Cook et al., 2003). Collision avoidance heavily relies on the sense of vision, in comparison to other senses such as audition (Souza Silva et al., 2018). For this reason, most of the literature has focused on the visual modality to infer the control variables involved (Cutting et al., 1995; Gerin-Lajoie et al., 2008; Olivier et al., 2012; Fajen, 2013; Darekar et al., 2018; Pfaff and Cinelli, 2018). VR has brought major contributions to our understanding of collision avoidance, with some elements that are especially relevant to rehabilitation. A first key element is that different collision avoidance strategies emerge when avoiding virtual objects vs. virtual humans. The latter were shown to lead to smaller obstacle clearances which were interpreted as a use of less conservative avoidance strategies (Lynch et al., 2018; Souza Silva et al., 2018). Factors that may explain such difference include the level of familiarity with the task (i.e., avoiding pedestrians is far more common than avoiding an approaching cylinder/sphere), the social attributes of the virtual humans (Souza Silva et al., 2018), as well as the local motion cues arising from the limb movements that were shown to shape some aspects of the avoidance strategy (Lynch et al., 2018; Fiset et al., 2020). A combination of real-world and VR studies has also shown that the collision avoidance strategy in response to a human interferer is modulated by factors such as the static vs. moving nature of the interferer (Basili et al., 2013) as well as its direction (Huber et al., 2014; Knorr et al., 2016; Buhler and Lamontagne, 2018; Souza Silva et al., 2018) and speed of approach (Huber et al., 2014; Knorr et al., 2016). All these factors can easily and effectively be manipulated in VR to promote the desired behavior and expose users to the diversity of scenarios they would encounter while walking in the community. Whether personal attributes of the interferers impact on collision avoidance strategies, however, is still unclear (e.g., Knorr et al., 2016; Bourgaize et al., 2020) and deserves further investigations.

VR-based studies on pedestrian interactions and collision avoidance, including recent work from our laboratory, have proven to be useful in unveiling the altered collision avoidance strategies experienced by several populations such as healthy older adults (Souza Silva et al., 2019; Souza Silva et al., 2020), individuals with mild traumatic brain injury (Robitaille et al., 2017), and individuals with stroke with (Aravind and Lamontagne, 2014; Aravind et al., 2015; Aravind and Lamontagne, 2017a; b) and without USN (Darekar et al., 2017b; a). We and others have also shown that simultaneously performing a cognitive task alters the collision avoidance behavior and can compromise safety by generating addition collisions (Aravind and Lamontagne, 2017a; Robitaille et al., 2017; Lamontagne et al., 2019a; Souza Silva et al., 2020; Deblock-Bellamy et al., 2021—accepted). In parallel to those clinical investigations, other studies carried out in healthy individuals have demonstrated that similar obstacle avoidance strategies are used when avoiding virtual vs. physical humans, although with subtle differences in walking speed and obstacle clearance (Sanz et al., 2015; Buhler and Lamontagne, 2018; Olivier et al., 2018; Bühler and Lamontagne, 2019). Such results support the use of virtual humans as a valid approach to evaluate and train pedestrian interactions as experienced in daily life. Pedestrian interactions can be facilitated by the use of omnidirectional treadmills that allow speed and trajectory changes (Lamontagne et al., 2019b; Soni and Lamontagne, 2020) and should be added as an essential dimension of community walking to complement existing VR-based interventions that focus on locomotor adaptations (e.g., Yang et al., 2008; Mirelman et al., 2011; Mirelman et al., 2016; Peruzzi et al., 2017; Richards et al., 2018).

DISCUSSION

A recent review (Tieri et al., 2018) of the contributions of VR to cognitive and motor rehabilitation suggests that the most promising effects of VR are the ability to multitask in a virtual environment that can replicate the demands of a physical environment, i.e., it is an ecologically valid rehabilitation tool.

Our data and others indicate that the sensory environment can be effectively manipulated to promote a desired motor outcome so that engagement with the task is encouraged and the process of active motor control is facilitated even if the VR environment deviates from physical reality. In order to accomplish this, however, we need to understand the properties of VR technology that create meaningful task constraints such as sensory conflict and error augmentation. One of the greatest weaknesses afflicting identification of the value of VR to rehabilitation is the application of the term "VR" to describe a myriad of paradigms that do not meet the requirements to truly be considered virtual reality. In order for a VR guided rehabilitation program to be successful, immersion in an environment that produces presence and embodiment is necessary if the user is to respond in a realistic way (Kenyon et al., 2004; Keshner and Kenyon, 2009; Tieri et al., 2018). Thus, only by activating the perception-action pathways for motor behavior will appropriate emotional reactions, incentives to act, and enhanced performance take place.

Results from the studies presented here clearly demonstrate that one of the primary contributions of VR to physical rehabilitation interventions is the ability to engage the whole person in the processes of motor learning and control (Sveistrup, 2004; Adamovich et al., 2009). Principal strengths of utilizing VR for rehabilitation is that it encourages motor learning through practice and repetition without inducing the boredom often resulting during conventional exercise programs. With this technology, interventions can be designed to address the particular needs of each individual, activity can be induced through observation, and intensity of practice can be modified in response to individual needs. But, in order to accomplish any of these goals, it is essential that the clinicians understand how and why they are choosing VR to meet their treatment goals and how to optimally tailor treatments for a desired outcome. Factors to consider when choosing to incorporate VR into a treatment intervention include whether (1) the donning of devices such as goggles alter motor performance (Almajid et al., 2020); (2) the manipulation of objects in the environment will alter the sense of presence; (3) certain populations are more susceptible to the virtual environment and, therefore, will respond differently than predicted (Slaboda et al., 2011b; Almajid and Keshner, 2019); and (4) a visual or multimodal presentation of the environment and task will be best to obtain the desired behavior. In addition, significant weaknesses remain in our understanding about the impact of VR on physical rehabilitation because of the dearth of well-designed clinical trials that consider dosages and technological equivalencies (Weiss et al., 2014).

In this article, we have focused on research demonstrating how multisensory signals delivered within a virtual environment will modify locomotor and postural control mechanisms. Studies using motor learning principles and complex models of sensorimotor control demonstrate that all sensory systems are involved in a complex integration of information from multiple sensory pathways. This more sophisticated understanding of sensory processing and its impact on the multisegmental body has altered our understanding of the causality and treatment of instability during functional movements. Therefore, incorporating VR and other applied technologies such as robotics has become essential to supplying the impact of multisensory processing on motor control (Saleh et al., 2017).

Motivation and enjoyment are an essential component in a rehabilitation program, and we are in no way suggesting that computer gaming and exercise and augmented reality technologies should be ignored because they do not necessarily deliver all components of a virtual reality environment. Rather, we are contending that there are additional pathways for training and modifying postural and locomotor behaviors in an immersive and multimodal virtual environment that will facilitate transfer of training of the neurophysiological and musculoskeletal mechanisms underlying functional motor behavior.

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Both authors have contributed equally to this work and share first authorship.

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SYSTEMATIC REVIEW
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System Immersion in Virtual Reality-Based Rehabilitation of Motor Function in Older Adults: A Systematic Review and Meta-Analysis

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Background: As the elderly population continues to grow, so does the demand for new and innovative solutions to tackle age-related chronic diseases and disabilities. Virtual Reality (VR) has been explored as a novel therapeutic tool for numerous health-related applications. Although findings frequently favors VR, methodological shortcomings prevent clinical recommendations. Moreover, the term "VR" is frequently used ambiguously to describe e.g., video games; the distinction remains vague between immersive VR (IVR) systems and non-immersive VR (NVR). With no distinct demarcation, results of outcome measures are often pooled in meta-analyses, without accounting for the immersiveness of the system.

Objective: This systematic review focused on virtual reality-based rehabilitation of older adults (+60) in motor rehabilitation programs. The review aims to retrospectively classify previous studies according to the level of immersion, in order to get an overview of the ambiguity-phenomenon, and to utilize meta-analyses and subgroup analyses to evaluate the comparative efficacy of system immersion in VR-based rehabilitation.

Methods: Following PRISMA guidelines, we conducted a systematic search for randomized controlled trials, describing virtual rehabilitation or video games interventions for older adults (+60). Main outcomes were pain, motivation, mobility, balance, and adverse events.

Results: We identified 15 studies which included 743 patients. Only three studies utilized IVR. The rest used various NVR-equipment ranging from commercial products (e.g., Nintendo Wii), to bespoke systems that combine tracking devices, software, and displays. A random effects meta-analysis of 10 studies analyzed outcome measures of mobility, balance, and pain. Protocols and dosage varied widely, but outcome results were in favor of immersive and non-immersive interventions, however, dropout rates and adverse events were mostly in favor of the control.

Conclusions: We initialize a call-for-action, to distinguish between types of VR-technology and propose a taxonomy of virtual rehabilitation systems based on our findings. Most interventions use NVR-systems, which have demonstrably lower cybersickness-symptoms than IVR-systems. Therefore, adverse events may be under-reported in RCT-studies. An increased demand for IVR-systems highlight this challenge. Care should be given, when applying the results of existing NVR tools to new IVR-technologies. Future studies should provide more detail about their interventions, and future reviews should differentiate between NVR and IVR.

Keywords: virtual reality, rehabilitation, immersive displays, older adults, balance, functional mobility, pain, systematic review

1. INTRODUCTION

By 2050 the world population is projected to reach 9.7 billion people, with older adults $\geq$65 accounting for approximately one fifth (1.7b) (United Nations, Department of Economic and Social Affairs). Increased life-expectancy implies a higher risk of developing various chronic diseases, including cardiovascular diseases, cancer, dementia, osteoarthritis, and stroke (Christensen et al., 2009; Fontana and Hu, 2014; Kennedy et al., 2014). Consequently, the diagnosis and treatment of these chronic diseases, which often require special care or hospitalizations, leads to rising expenditures for the healthcare systems around the world (United Nations, Department of Economic and Social Affairs). As an approach to prevent these trends, it has been suggested that increased physical activity, as regular exercising provides multiple health benefits, and reduces the risk of obtaining chronic diseases (Duncan et al., 2010; Anderson and Durstine, 2019; De la Rosa et al., 2020).

Despite evidence for the health benefits of keeping active, low motivation is often a challenge when seeking to counteract physical inactivity and sedentary lifestyles, through exercise programs (Teixeira et al., 2012). In the context of rehabilitative interventions, outcomes, and recovery often depend on the patient's motivation, leading programs to suffer from low adherence as a consequence. This has been identified as a challenge within different fields of rehabilitation, including pulmonary rehabilitation (Bourbeau and Bartlett, 2008; Salinas et al., 2011), acute stroke (Maclean et al., 2000), and diabetes (Rizzo et al., 2011).

Novel technologies such as active video games and virtual reality (VR) technologies, when used appropriately, have the potential to solve some of the challenges with low motivation and adherence. However, implementation into clinical practice has not yet been fully realized. On the other hand, VR has seen a commercial breakthrough within the last 5 years, and steadily increased the technological awareness of consumers and health professionals (Keshner et al., 2019). Within this field of rehabilitation, the therapeutic effects and value of VR technologies has been evaluated and scrutinized for over two decades, often under the general term of *Virtual Rehabilitation* (Burdea, 2003; Tieri et al., 2018). Within this highly specialized and diverse field, VR has successfully been applied to rehabilitation for adults with simple phobias (Rothbaum et al., 2006; Parsons and Rizzo, 2008; Powers and Emmelkamp, 2008; Maples-Keller et al., 2017); Post-traumatic stress disorder (PTSD); (Rothbaum et al., 2001; Difede et al., 2007; Kothgassner et al., 2019); acute and chronic pain treatment (Gold et al., 2005; Hoffman et al., 2008; Li et al., 2011; Pourmand et al., 2018; Matamala-Gomez et al., 2019; Wittkopf et al., 2020); post-stroke treatment, brain injury, and various other forms of neurological disorders (Rizzo et al., 2004; Rose et al., 2005; Stewart et al., 2007; Laver et al., 2017; Karamians et al., 2020).

For motor rehabilitation as an example, advantages with immersive characteristics of VR include how the sense of presence can induce an illusion of virtual body ownership and agency through multisensory feedback (Kilteni et al., 2015). The sensorimotor loops needed for motor rehabilitation can be strengthened through the introduction of a virtual context, to connect relevant cognitive associations to otherwise isolated repetitive motor tasks (Tieri et al., 2018). This is highly relevant in rehabilitation to reestablish cognitive function processes as motor skills, for instance with stroke patients (de Bruin et al., 2010). For geriatric rehabilitation, virtually augmented exercise is similarly proposed to influence cognitive abilities, for instance in cases including dementia (Garcia-Betances et al., 2015).

Nevertheless, VR remains an umbrella term within the field of rehabilitation, used to describe many and vastly different technologies, from "non-immersive" single desktop displays to "immersive" high fidelity motion-sensing input devices and wearable technologies such as head-mounted displays (HMDs) (Tieri et al., 2018). Hardware aside, variations between software solutions used to study the efficacy of "VR-based" rehabilitation (Burdea, 2003) (VRBR) is equally pluralistic. Hence, attempting to define VR, entails a certain ambiguity across a large body of research. However, interventions rarely use immersive VR (IVR)-technology as a facilitator (Tieri et al., 2018).

1.1. Current Systematic Reviews

In systematic reviews exploring the efficacy of virtual systems, VR is likewise ambiguously defined, and is frequently specifically defined as the use of commercial non-immersive consoles such as Nintendo Wii (Donath et al., 2016). Systematic reviews have explored the use of VR for improving mobility and balance (Donath et al., 2016; Neri et al., 2017; Amorim et al., 2018; Porras et al., 2018), physical functioning (Molina et al., 2014) and in general, to improve health-related domains (Miller et al., 2014). However, included articles frequently only describe interventions using NVR; again, most commonly using the Nintendo Wii (Miller et al., 2014; Molina et al., 2014; Amorim et al., 2018; Reis et al., 2019). For example, of the 10 articles included in Amorim et al.'s review (Amorim et al., 2018), 6 use Nintendo Wii console, while the remaining used Playstation EyeToy ($n = 1$), Xavis measured step system ($n = 1$), or bespoke systems with pressure mats or balance boards ($n = 2$). Likewise, of the 13 articles included in the review by Molina et al. (2014), most used Nintendo Wii (Fit) ($n = 8$), Balance Rehabilitation Unit from Medicaa ($n = 1$), or video games or bespoke systems ($n = 4$). Indeed, in a recent review by Karamians et al. (2020), exploring the effectiveness of VR and gaming-based interventions for UE post-stroke rehabilitation, only three of the included 38 articles described IVR technology. And while the authors are well aware of the distinguishing features of VR-systems (Karamians et al., 2020), this crucial differentiation may easily be lost, if the review is included in future syntheses. While findings frequently demonstrate a significant improvement in favor of virtual rehabilitation (for example Neri et al., 2017, $P < 0.01$), the quality of the evidence is often low with a high *risk-of-bias* (RoB) (Laver et al., 2012; Donath et al., 2016; Neri et al., 2017; Amorim et al., 2018). Therefore, the need remains to explore the efficacy of virtual rehabilitation in larger and better controlled studies.

Previous attempts have sought to delimit VR, by simply referring to devices which utilize *immersive technology* (Iosa et al., 2012; Rizzo and Koenig, 2017; Tieri et al., 2018). However, "immersion" has likewise seen its share of ambiguous usage, and is often confused with related terms, such as *presence* (Nilsson et al., 2016). VR-systems of high fidelity (e.g., HMDs), are usually referred to as fully immersive VR, or simply immersive VR (IVR). Lower fidelity systems are in these cases mostly referred to as non-immersive VR (NVR). For clarification, we will outline these aspects, before commencing the review's methodology.

1.2. Defining Immersion

VR can be described as a computer-generated interactive virtual environment. The defining feature separating VR from traditional media, is arguably VR's ability to give users a compelling illusion of "being there" in virtual environments. This illusion is often referred to as *presence* or *place illusion* (Slater, 2009), and has been described as the subjective correlate of immersion (Slater and Sanchez-Vives, 2016). Place illusion describes the subjective experience of a user, whereas immersion relates to objective characteristics of the system used to deliver this experience. The more immersive a system is, the higher degree of presence it can elicit. Immersive systems have been characterized based on the sensorimotor contingencies (SCs) they support (Slater, 2009). SCs are the actions a person can perform in order to perceive the world (e.g., changing one's gaze direction by moving the head or eyes, or kneeling to see underneath something). The level of immersion supported by a given VR-system depends on how well it supports normal SCs. Therefore, in this review, when discussing immersion, we operate with the term "system immersion" (Nilsson et al., 2016). A number of factors related to both displays and tracking can affect system immersion, however, for the purpose of the current review, we adopt a simple dichotomous categorization with respect to immersion. Level of immersion is distinguished between two broad categories of systems: *immersive systems* and *non-immersive systems*. Immersive systems allow users to view virtual content in all directions (i.e., they have an unlimited field of regard, FOR), even though the field of view (FOV) usually is smaller than the users visual field. Contrarily, non-immersive systems only offer a limited FOR and a limited FOV (e.g., screen- and projection-based systems).

1.3. Specific and Non-specific Systems

When the Nintendo Wii launched in 2006, it quickly became an affordable closed system, that supported physical activity with games and entertainment, with researchers soon after applying it to physical therapy programs (Deutsch et al., 2008). This caused a shift from bespoke systems (i.e., software and hardware solutions created for specific users and contexts) toward commercially available solutions (Keshner et al., 2019). A recent systematic review exploring types of VR applications within rehabilitation, characterize these different systems dichotomously as either specific (systems specifically built for rehabilitation) or non-specific (i.e., computerized systems meant for recreational activities and gaming) (Maier et al., 2019). However, systems can be simultaneously commercial and specific. This is evident from the increasing amount of companies developing high-end equipment, where gamification principles are embedded into the therapy (IREX, VRRS-systems, and others; Maier et al., 2019). Systems can also be custom-built from existing hardware and software, tailored for specific needs (i.e., bespoke systems). We argue that a distinction has to be made between commercial and bespoke systems, since low availability and accessibility of certain VR-systems challenges the reproducibility of findings or clinical applications. This is most commonly a trait of bespoke systems, which are usually developed in closed ecosystems, specifically to solve contextual challenges. Conversely, commercially available "off-the-shelf" systems can more reliably reproduce results. This means that cross-study analyses would gain a homogeneous data sets, and that any heterogeneity found in e.g., meta-analyses, would more confidently be attributed to sampling error.

1.4. The Potential Challenges of Ambiguous Classifications

The caveat to IVR and a main reason why a clear distinction is important for systematic reviews, is how the technology leads to demonstrably larger levels of side-effects, when compared to conventional displays (Sharples et al., 2008; Kim et al., 2014; Dennison et al., 2016; Chang et al., 2020). These side effects are also known as *VR-sickness, cybersickness, VR-induced symptoms, and effects* (VRISE) (Sharples et al., 2008), or *visually induced motion sickness* (Rebenitsch and Owen, 2016). In a study from 2008, Sharples et al. compared side-effects between different display technologies, including HMD, desktop monitor and projection screens (Sharples et al., 2008). The results indicated a significant increase in nausea symptoms when using HMD, compared to desktop and projection screens. Technology has progressed substantially since 2008, by including improved frame rate- and refresh rates frequencies to accommodate human-eye resolution and sensorimotor contingencies (LaViola, 2000). However, cybersickness remains an unsolved problem with IVR technology. A commonly used measure of VR-sickness is the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993). While ironically not developed for IVR, it is a frequently used, standardized and validated measure of the severity of symptoms related to nausea, oculomotor disturbances and disorientation, while using a VR-system. It has also previously been used to measure adverse events related to VRBR-use (Dahdah et al., 2017), although often reported incorrectly. Additionally, it has been suggested that only IVR-technology should be defined as VR (Tieri et al., 2018). More specifically, solutions utilizing non-immersive technologies to facilitate an immersive and interactive digital environment. We agree with Tieri et al. (2018), therefore, another aim our work is to propose a model to better classify the use of VR-equipment in clinical contexts.

This review seeks to distinguish between the broader uses of VR, which encompasses non-immersive VR (NVR), for example video games and consoles such as Nintendo Wii, and the more discrete use of IVR, where the "immersion" is a property of the technical system (Nilsson et al., 2016) such as with HMDs. Like Tieri et al. (2018), we believe taxonomic consistency is more pertinent now than it was previously, as the availability of commercial IVR-systems will continue to increase the demand for clinical applications. Paradoxically, the evidence in favor of the safety, affordance, feasibility, efficacy, and implementation within clinical use, is still in its infancy. Furthermore, a classification of VRBR solutions for clinical application is needed, to frame such evidence and to allow practitioners suitable awareness, before including solutions into daily practice. And since the geriatric population is the largest group with rehabilitation needs, this is a good place to commence.

1.5. Research Questions

This review focuses on VRBR of older adults (+60) in motor rehabilitation programs. The aim of this review is to:

1. Retrospectively classify previous studies according to level of immersion, in order to get an overview of the ambiguity-phenomenon.
2. Utilize meta-analyses and subgroup analysis to determine outcome effect variations between IVR and NVR
3. Evaluate the comparative effectiveness of system immersion in IVR and NVR systems
4. Analyze comparative risks and adverse events between IVR and NVR systems.

2. METHODS

The systematic review protocol was registered in PROSPERO (ID: CRD42019121172), and the reporting of the review was conducted following the *Preferred Reporting Items for Systematic Reviews and Meta-Analysis* (PRISMA) guidelines (Liberati et al., 2009).

2.1. Eligibility Criteria

The selection of studies were conducted based on prespecified PICOS (participants, interventions, comparisons, outcomes, and study design) (Liberati et al., 2009):

- **Participants:** older adults (≥60 years old).
- **Intervention:** VR-based motor rehabilitation (e.g., for non-neurological muscular dysfunction, replacement surgery, prosthetic adaptation, or traumatic injuries).
- **Comparison:** conventional therapy or usual care.
- **Outcome:** Mobility and balance, motivation, pain, and adverse events (e.g., cybersickness, fall injuries, dizziness, eye strain, or other reported adverse incidents).
- **Study design:** Randomized Controlled Trials (RCT). Both parallel - and crossover groups.

2.2. Information Sources

The systematic search was undertaken on the following databases: PubMed/MEDLINE, Web of Science, CINAHL, Cochrane Library, and EMBASE to find articles describing randomized controlled trials (RCT), published in English, Danish, Swedish, or Norwegian.

2.3. Search

The search strategy was developed by and approved by all authors. The searches were performed by SMF and SWH who (1) extracted studies from the databases into EndNote; (2) performed duplicate removal; (3) uploaded them into Covidence for screening. All databases were searched from inception to the 30th April 30, 2020.

Search strings were adapted to fit each database individually using boolean search operators and limited to *Human studies* and *Randomized Controlled Trials* whenever possible. Search themes included rehabilitation or physical therapy using virtual reality, "exergames" or video games. A broad search for video games as well was to not only search for interventions describing non-immersive applications. A full list of all searches performed can be found in the **Supplementary Material**.

2.4. Study Selection

Title and abstract screening was performed by ERH and TMP; articles were excluded based on the following criteria: no full text available, wrong language, not peer-reviewed, wrong study design, wrong study population (participants are healthy adults, under the age of 60 or principle diagnosis was neurological), wrong outcomes or wrong setting.

A blinded full-text screening was performed independently by two reviewers (ERH and TMP). Conflicts were resolved by ERH and TMP through discussion, or with arbitration by third reviewer (KBJ).

2.5. Data Collection Process

Quantitative data was extracted from the included studies by pairwise independent reviewers (ERH, TMP, KBJ, JPE, and NCN) using a standardized data extraction form, which was presented and agreed upon at a joint meeting. Inter-rater conflicts in the data extraction process was resolved by ERH and TMP in consensus.

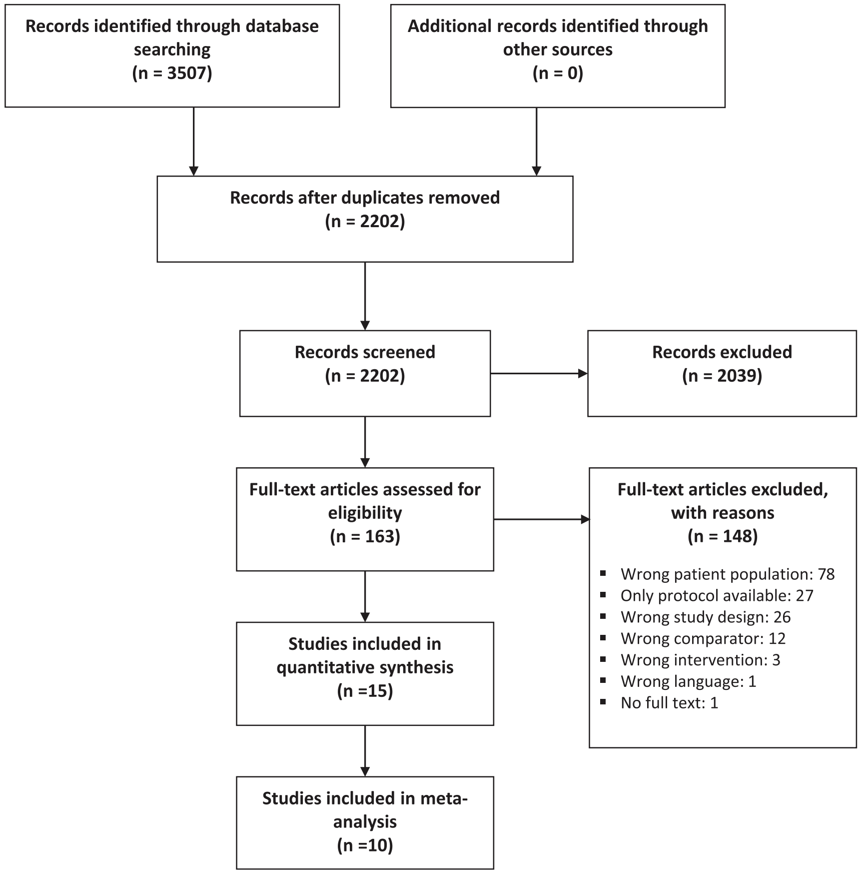

FIGURE 1 | The PRISMA flow diagram for the systematic review detailing the selection process of the included RCT studies.

2.6. Assessment of Risk of Bias in Included Studies

We utilized the Cochrane Collaboration's RoB Tool (Liberati et al., 2009) to evaluate the methodological quality of the included studies. RoB assessment was independently performed by two paired reviewers (ERH, TMP, NCN, JPE, and KBJ). Conflicts were resolved by ERH and TMP.

2.7. Data Analysis

Results from the different trials were pooled using RevMan 5.4 (The Nordic Cochrane Centre, The Cochrane Collaboration, 2020). The primary outcomes for balance was determined as either timed tasks such as Timed Up and Go (TUG), or composite scores such as the Berg's Balance Scale (BBS). For functional mobility, the outcomes were limited to timed tasks such as the six minute walk test (6mWT) or the 10 meter walk test (10mWT). Pain-measurements were limited to standardizable self-reported uni-dimensional measures, such as visual analog scales (VAS), numerical rating scales (NRS). To estimate effect sizes of outcomes, we used standard mean difference (SMD) for different (or variations of the same) instruments, including VAS and BBS. For studies using similar instruments the mean difference (MD) was used.

Random-effects were used for all analyses, as the included populations were likely not functionally equivalent, since the interventions described different outcomes and patient populations. Variability within studies are reported in forest plots. Subgroup analysis to determine differences between IVR and NVR studies were performed. Due to the low amount of IVR-studies, subgroup analysis was only undertaken for pain. Heterogeneity was assessed individually for each outcome and considered insignificant if the I^2 value was beneath a moderate level $>$50% as suggested by Higgins and Thompson (2002). Effects are considered statistically significant if $p \leq 0.05$. All analyses use End of Treatment (EoT) scores.

3. RESULTS

3.1. Study Identification

Through the different databases, we identified 3,507 articles matching the search strategy. No additional records were identified. After removing duplicates, 2,202 articles were screened, and 2,039 articles were excluded based on title and abstract, because they did not match the inclusion criteria. The full search strategy is outlined in **Figure 1**. Many of the excluded articles described interventions that did not include virtual rehabilitation. Among the most frequent occurrences were interventions with cold-water immersion. One hundred and sixty-three articles published between 1999 (Kim et al., 1999) and April 2020 were assessed for eligibility and 15 articles ($n = 743$) satisfied the inclusion criteria and 10 ($n = 555$) articles satisfied the correct outcomes required for conducting a meta-analysis.

Of the 15 included articles describing RCT interventions (see **Table 1**), two studies used specific commercial IVR technology (Duque et al., 2013; Gianola et al., 2020), one study used a specific commercial NVR system (Nirvana VR system) (Yeşilyaprak et al., 2016) and one intervention used a bespoke specific system (Jin et al., 2018). Six studies used NVR non-specific commercial systems, either Nintendo Wii Fit (Laver et al., 2012; Fu et al., 2015; Sobral Monteiro-Junior et al., 2015; Kwok and Pua, 2016; Morone et al., 2016; Tsang and Fu, 2016) or Sony Playstation with Eye Toy (Lee and Shin, 2013), and four studies used specific bespoke systems (Schwenk et al., 2016; Mugueta-Aguinaga and Garcia-Zapirain, 2017; Oesch et al., 2017; Anson et al., 2018). Of the included studies, 13 referred to "virtual reality" while only two did not mention virtual reality, but referred to "exergames" (Mugueta-Aguinaga and Garcia-Zapirain, 2017; Oesch et al., 2017). All IVR studies referred to the intervention as "VR" (Duque et al., 2013; Jin et al., 2018; Gianola et al., 2020), and four NVR studies referred to the intervention as "VR" (Lee and Shin, 2013; Sobral Monteiro-Junior et al., 2015; Kwok and Pua, 2016; Yeşilyaprak et al., 2016) while the remaining studies described the intervention as *interactive gaming* (Laver et al., 2012) or *exergames* (Mugueta-Aguinaga and Garcia-Zapirain, 2017; Oesch et al., 2017); *visual feedback* (Anson et al., 2018) or *sensor-based balance training* (Schwenk et al., 2016) and *Wii Fit Training/Wii exercise* (Fu et al., 2015; Morone et al., 2016; Tsang and Fu, 2016). Two articles used "virtual reality" in the title or abstract, but provided very limited mention of VR in the full-text (Tsang and Fu, 2016; Anson et al., 2018), and VR was not mentioned as part of the intervention. Authors were contacted for two articles to clarify system specific details. Both contacts responded within 4 months.

Participants and settings varied across the included articles. Four articles recruited older adults living in residential aged care (Fu et al., 2015; Tsang and Fu, 2016; Yeşilyaprak et al., 2016; Mugueta-Aguinaga and Garcia-Zapirain, 2017). Older adults with balance difficulties living in the community were the focus of three articles (Duque et al., 2013; Morone et al., 2016; Anson et al., 2018). Two articles recruited participants following total knee arthroplasty (Jin et al., 2018; Gianola et al., 2020). Frail older adults were recruited in one study (Kwok and Pua, 2016). A range of different diagnoses in the inpatient setting were the focus of two studies (Laver et al., 2012; Oesch et al., 2017). Chronic conditions such as diabetes mellitus (Lee and Shin, 2013), peripheral neuropathy (Schwenk et al., 2016), and chronic low back pain (Sobral Monteiro-Junior et al., 2015). Dosage of the interventions varied as well between 20 and 90 min per session (mean $\pm$ SD: 43.7 $\pm$ 19.8), between 1 and 5 weekly sessions (2.7 $\pm$ 1) for durations between 3 and 12 weeks (6.6 $\pm$ 2.7).

3.2. Mobility and Balance

A range of outcome-measures were used. The most commonly used outcomes for mobility and balance were Timed Up and Go (TUG) (Laver et al., 2012; Lee and Shin, 2013; Kwok and Pua, 2016; Tsang and Fu, 2016; Yeşilyaprak et al., 2016; Anson et al., 2018), Berg Balance Scale (BBS) (Laver et al., 2012; Lee and Shin, 2013; Morone et al., 2016; Tsang and Fu, 2016; Yeşilyaprak et al., 2016; Anson et al., 2018), and six-minute walk test (6MWT) (Kwok and Pua, 2016; Anson et al., 2018). Other measures included posturography (Duque et al., 2013; Schwenk et al., 2016; Oesch et al., 2017), short physical performance battery (SPPB) (Duque et al., 2013; Fu et al., 2015; Mugueta-Aguinaga and Garcia-Zapirain, 2017), and fall risk (Fu et al., 2015). Six studies were included in the meta-analysis for the overall effect of NVR (VFB treadmill, Nintendo Wii, Playstation 2 + EyeToy, NIRVANA VR Interactive System) on TUG scores as a measure of dynamic balance (**Figure 2**). The mean time to complete the TUG ranged from 9.1 ($\pm$1.1) s to 28.86 ($\pm$11.71) s across the studies. The MD between experimental and control groups ranged from 0.23 to 1.11 s. Considerable heterogeneity was found between studies ($Tau^2 = 0.08$, $Chi^2 = 15.50$, df = 5, $I^2 = 68\%$, df = 5). Compared to the control group, the SMD between groups on TUG scores was significantly greater for the VR group, demonstrating a significant treatment effect ($Z = 1.94$, $p = 0.05$).

Six studies were included in the meta analysis for the overall effect of NVR (VFB treadmill, Nintendo Wii Fit, Playstation 2 + EyeToy, NIRVANA VR Interactive System) on BBS scores as a measure of balance (**Figure 3**). The mean BBS scores ranged from 30.1 ($\pm$8.84) to 53.41 ($\pm$1.49) across the studies. The MD between experimental and control groups ranged from 0 to –2.49 s. Considerable heterogeneity was found between studies ($Tau^2 = 0.96$, $Chi^2 = 9.03$, df = 5, $I^2 = 45\%$, df = 5). Compared to the control group, the SMD between groups on BBS scores was significantly greater for the VR group, demonstrating a significant treatment effect ($Z = 4.02$, $p \leq 0.0001$).

Two studies were included in the meta-analysis for the overall effect of NVR (VFB treadmill, Nintendo Wii Fit) on 6MWT scores (**Figure 4**). The mean 6MWT scores ranged from 323.7 ($\pm$25.9) s to 387.8 ($\pm$70.8) s across the studies. Considerable heterogeneity was found between studies ($Tau^2 = 0.00$, $Chi^2 = 0.73$, df = 1, $I^2 = 0\%$). Compared to the control group, the SMD between groups on 6MWT scores was not significantly different between the VR group and control group ($Z = 1.85$, $p = 0.06$).

3.3. Motivation

Adherence, enjoyment and motivation were measured in only one study (Oesch et al., 2017). The primary outcome of the study was the adherence to exercise as measured by the duration of exercise each day. Motivation and enjoyment were measured after each training using a five-point Likert scale. Each of these outcomes, adherence, motivation, and enjoyment were found to be favored in the conventional exercise group. Another study measured game satisfaction on a custom dichotomous scale with direct "yes/no" questions, but only for the experimental group (Mugueta-Aguinaga and Garcia-Zapirain, 2017).

3.4. Pain

Two studies were included in the meta-analysis for the overall effect of IVR (Khymeia VRRS, HTC Vive) on pain scores for patients following total knee arthroplasty. The SMD between

TABLE 1 | Characteristics of included articles.

References	Population	N (% male);	Mean (SD) age	Country	Main outcomes	Dosage mm/d (w)	Comparison	VR system	Classification
Anson et al. (2018)	Older adults with balance difficulties	40 (27.5)	75.7 (5.8)	USA	Improve balance	30 / 3 (4)	Treadmill without visual feedback	TV-screen and threadmill	NVR-S (B)
Gianola et al. (2020)	Patients with total kneee arthroplasty	74 (43.5)	68.8 (8.8)	Italy	Increase efficacy of early rehab, decrease pain intensity	60 ("5 days")	Passive knee motion on Kinetec knee continuous passive motion system	Khymeia VRRS	IVR-S (C)
Jin et al. (2018)	Osteoarthritis patients with total knee arthroplasty	66 (42)	66.4 (3.9)	China	Decrease pain and improve knee range-of-motion	30*3 / - (-)	Exercise program	HMD (Mide Technology Inc.)	IVR-S (B)
Kwok and Pua (2016)	Frail older adults	73 (30)	70.1 (7.1)	Singapore	Improve functional outcomes and fear of falling	20 / 1 (12)	Gym exercise class + home exercise	Nintendo Wii Active + Wii Balance Board	NVR-NS (C)
Laver et al. (2012)	Inpatients with different admission diagnoses	42 (20.4)	84.9 (4.5)	Australia	Investigate feasibility and clinical outcomes for mobility	25 / 5 (-)	Matched activities for the duration of the stay	Wii Fit + wireless pointer	NVR-NS (C)
Lee and Shin (2013)	Older adults with diabetes mellitus	55 (29.1)	74 (4.9)	South Korea	Improve balance, strength, gait and fall efficacy	50 / 2 (10)	Health education on diabetes management	PlayStation 2 + EyeToy	NVR-NS (C)
Sobral Monteiro-Junior et al. (2015)	Older women with chronic low back pain	30 (0)	68 (4)	Brazil	Decrease chronic pain, increase physical capabilities and mood	90 / 3 (8)	Strength exercise	Nintendo Wii + Wii Balance Board	NVR-NS (C)
Morone et al. (2016)	Women with bone loss conditions due to balance disorders	38 (0)	68.9 (4.2)	Italy	Improve balance, quality of life, fear of falling and well-being	60 / 2 (8)	Conventional exercise and balance training	Nintendo Wii Fit	NVR-NS (C)
Tsang and Fu (2016)	Older adults living in aged care facilities	79 (39)	82.1 (4)	China	Improve balance control in older adults	60 / 3 (6)	Conventional balance training	Nintendo Wii Fit	NVR-NS (C)
Yeşilyaprak et al. (2016)	Older adults living in nursing homes	18 (33.3)	71.9 (4.5)	Turkey	Increase balance and reduce risk of falls	45 / 3 (6)	Conventional balance exercise	NIRVANA VR Interactive System	NVR-S (C)
Duque et al. (2013)	Older adults with balance difficulties	68 (39)	76.8 (9.1)	Australia	Improve balance, reduce risk of falls and fear of falling	30 / 2 (6)	Usual care	BRU balance training	IVR-S (C)
Fu et al. (2015)	Frail older adults from nursing home	60 (35)	82.4 (4)	China	Reduce risk and incidence of falls	60 / 3 (6)	Usual care	Nintendo Wii Fit	NVR-NS (C)
Mugueta-Aguinaga and Garcia-Zapirain (2017)	Older adults from residential homes	39 (40)	84.3 (7.8)	Spain	Reduce frailty risks	20 / "9" (3)	No activity	Kinect + FRED exergame	NVR-S (B)
Schwenk et al. (2016)	Older cancer patients with chemotherapy-induced peripheral neuropathy	22 (41)	70.3 (8.7)	USA	Improve postural balance	45 / 2 (4)	No exercise intervention	Wearable sensors	NVR-S (B)
Oesch et al. (2017)	Geriatric inpatients	39 (53.7)	IG: 73.8* (-)	Switzerland	Improve adherence and motivation	2x30 ("10 days")	Instruction leaflets	Kinect-based	NVR-S (B)

*N, sample size; SD, standard deviation; "-", missing data; *, median/IQR reported; IG, intervention group; dosage, minutes per session/days per week (total weeks); NVR, Non-immersive VR; IVR, Immersive VR; S, Specific; NS, Non-specific; B, Bespoke; C, Commercial.*

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
1.4.1 Non-immersive								
Anson 2018	10.1	2.9	20	11.2	2.9	20	16.6%	-1.10 [-2.90, 0.70]
Kwok 2016	9.1	1.1	37	9.1	1.2	36	29.0%	0.00 [-0.53, 0.53]
Laver 2012	27.9	10.44	22	28.86	11.71	22	2.5%	-0.96 [-7.52, 5.60]
Lee 2013	9.78	1.58	27	12.27	2.87	28	22.2%	-2.49 [-3.71, -1.27]
Tsang 2016	17	2.8	39	18.2	2.4	40	23.0%	-1.20 [-2.35, -0.05]
Yeilyaprak 2016	9.6	4	7	10	3.7	11	6.7%	-0.40 [-4.08, 3.28]
Subtotal (95% CI)			**152**			**157**	**100.0%**	**-1.06 [-2.14, 0.01]**

Heterogeneity: Tau² = 0.96; Chi² = 15.50, df = 5 (P = 0.008); I² = 68%
Test for overall effect: Z = 1.94 (P = 0.05)

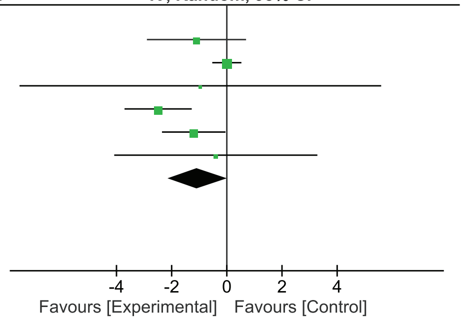

FIGURE 2 | Forest plot of outcome measures for balance assessment using timed tasks, specifically timed up-and-go (TUG), for VR-based therapy vs. control (EoT).

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.3.1 Non-immersive								
Anson 2018	52.5	2.7	20	51.9	3.4	20	16.9%	0.19 [-0.43, 0.81]
Laver 2012	32.1	6.57	22	30.29	8.84	22	17.8%	0.23 [-0.36, 0.82]
Lee 2013	53.41	1.89	27	51.14	2.84	28	18.9%	0.92 [0.37, 1.48]
Morone 2016	50.7	1.9	19	47.8	3.7	19	15.3%	0.97 [0.29, 1.64]
Tsang 2016	40.7	3.2	39	37.8	1.8	40	21.9%	1.11 [0.63, 1.59]
Yeilyaprak 2016	54.4	3.4	7	51.8	3.9	11	9.2%	0.67 [-0.31, 1.64]
Subtotal (95% CI)			**134**			**140**	**100.0%**	**0.70 [0.36, 1.04]**

Heterogeneity: Tau² = 0.08; Chi² = 9.03, df = 5 (P = 0.11); I² = 45%
Test for overall effect: Z = 4.02 (P < 0.0001)

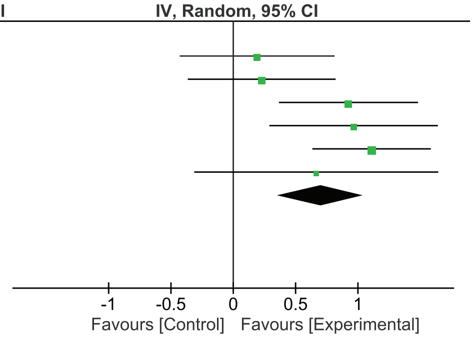

FIGURE 3 | Forest plot of outcome measures for balance assessment using Berg Balance Scale (BBS) for VR-based therapy vs. control (EoT).

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
1.6.1 Non-immersive								
Anson 2018	387.8	70.8	20	377.6	88.9	20	5.5%	10.20 [-39.61, 60.01]
Kwok 2016	323.7	25.9	37	335.9	26.3	36	94.5%	-12.20 [-24.18, -0.22]
Subtotal (95% CI)			**57**			**56**	**100.0%**	**-10.98 [-22.62, 0.67]**

Heterogeneity: Tau² = 0.00; Chi² = 0.73, df = 1 (P = 0.39); I² = 0%
Test for overall effect: Z = 1.85 (P = 0.06)

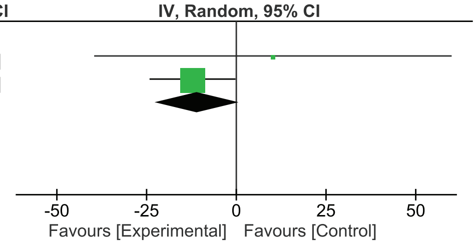

FIGURE 4 | Forest plot of timed tasks, specifically 6MWT, for functional mobility outcome measures for VR-based therapy vs. control (EoT).

groups on pain scores was significantly greater for the VR group, demonstrating a significant treatment effect ($Z = 2.57$, $p = 0.01$). Two studies were included in the meta-analysis for the overall effect of NVR (Nintendo WiiFit) on pain scores for people with chronic low back pain and balance disorders. There was no significant difference between the NVR and control groups ($Z = 0.78$, $p = 0.44$). Comparison of IVR and NVR demonstrated no significant difference in overall treatment effect between type of VR ($Z = 1.03$, $p = 0.02$) (**Figure 5**).

3.5. Adverse Events and Dropouts

Two studies mentioned that adverse events were observed during the intervention (Laver et al., 2012; Oesch et al., 2017), and five articles mentioned that no adverse events were detected (Kwok and Pua, 2016; Schwenk et al., 2016; Yeşilyaprak et al., 2016; Anson et al., 2018; Gianola et al., 2020). The majority of the studies made no specific mention of adverse events (Duque et al., 2013; Lee and Shin, 2013; Fu et al., 2015; Sobral Monteiro-Junior et al., 2015; Morone et al., 2016; Tsang and Fu, 2016; Mugueta-Aguinaga and Garcia-Zapirain, 2017; Jin et al., 2018).

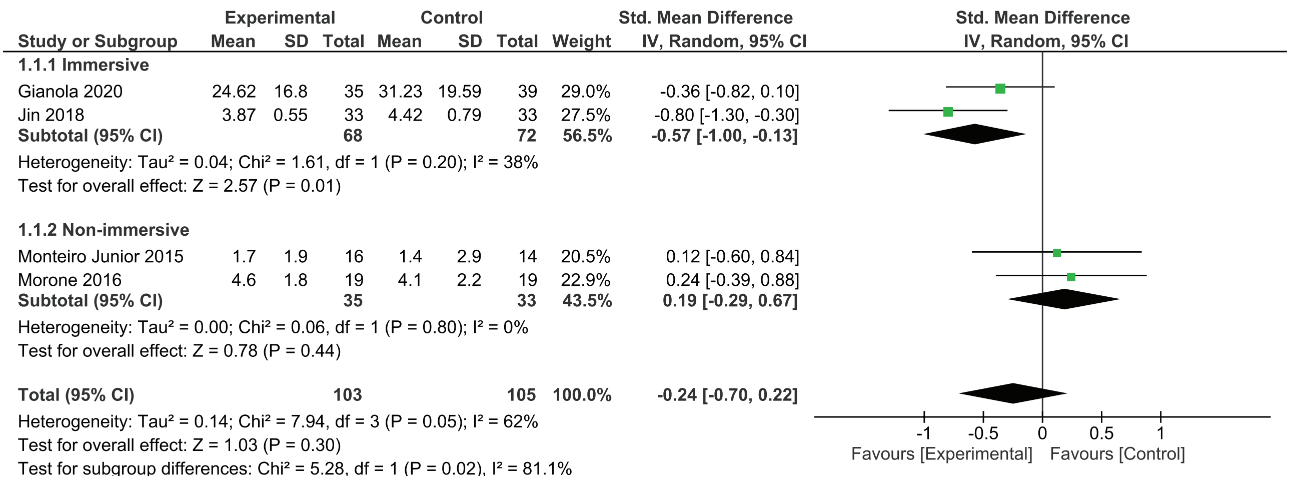

FIGURE 5 | Forest plot of studies measuring pain intensity through unidimensional measures, using a visual analog scale (VAS), for VR-based therapy vs. control (EoT).

Dropouts varied across studies and interventions (**Figure 6**). The absolute risk of the experimental group was 41 vs. 20 for the control groups. The weighted average dropout rate was 10% for experimental groups and 5% for control groups. The highest number of dropouts were seen in Oesch et al. (2017) 11/28 in the experimental group, whereas the authors identify 7 dropouts related to the treatment either due to dislike ($n = 5$) or experience of pain ($n = 2$).

3.6. Risk of Bias Assessment

The risk of bias analysis was performed to assess the methodological quality of the articles included in the quantitative synthesis. The resulting summary can be seen in **Figure 7**. No additional sources of bias were discovered.

3.6.1. Selection Bias

All studies except two (Kwok and Pua, 2016; Jin et al., 2018) described a random component when allocating participants to groups (sequence generation). However, six of the included studies did not conceal allocation when assigning participants to the intervention groups (allocation concealment) assessed as a high risk (Lee and Shin, 2013; Sobral Monteiro-Junior et al., 2015; Tsang and Fu, 2016; Yeşilyaprak et al., 2016; Anson et al., 2018; Jin et al., 2018).

3.6.2. Performance Bias

Blinding of participants and personnel is almost always impossible in physical health research (Karanicolas et al., 2010), which is also reflected in all of the study receiving a high risk assessment.

3.6.3. Detection Bias

While blinding of participants or personnel is impossible, blinding of outcome assessors is still feasible. However, half of the studies (Lee and Shin, 2013; Morone et al., 2016; Tsang and Fu, 2016; Yeşilyaprak et al., 2016; Jin et al., 2018) reported that outcomes were assessed by the same people who performed the experiment which we estimate as a high risk. One study (Kwok and Pua, 2016) did not specify details (unknown risk) and four studies (Laver et al., 2012; Sobral Monteiro-Junior et al., 2015; Anson et al., 2018; Gianola et al., 2020) took steps to blind outcome assessors (low risk).

3.6.4. Attrition Bias

Concerning incomplete outcome data, three studies had no missing data (Morone et al., 2016; Tsang and Fu, 2016; Jin et al., 2018), (low risk, see also **Figure 6**). Two studies reported dropouts, but outcomes were calculated based the number of participants, and intention-to-treat was used to account for missing data (Laver et al., 2012; Morone et al., 2016) (low risk). Two studies (Lee and Shin, 2013; Anson et al., 2018) had a low and slightly disproportionate dropout-rate in favor of the control group, however performed a per-protocol analysis (uncertain risk). Three studies (Sobral Monteiro-Junior et al., 2015; Yeşilyaprak et al., 2016; Gianola et al., 2020) had moderate dropouts, disproportionately in favor of the control group, and conducted a per-protocol analysis with no attempts at an intention-to-treat analysis (high risk).

3.6.5. Reporting Bias

We did not compare trial protocols with published outcomes, therefore intervention effects could be overestimated. Selective outcome reporting was assessed based on whether or not the articles made a reference to an existing protocol. Only three studies referenced a prospectively registered trial protocol (Sobral Monteiro-Junior et al., 2015; Anson et al., 2018; Gianola et al., 2020), two studies were retrospectively registered (Laver et al., 2012; Kwok and Pua, 2016), and five studies made no reference to a protocol receiving a high risk assessment (Lee and Shin, 2013; Morone et al., 2016; Tsang and Fu, 2016; Yeşilyaprak et al., 2016; Jin et al., 2018). We justify an unknown risk for retrospectively registered trials because reported outcomes in the registry technically could reflect findings of the study, which could also indicate overestimated intervention effects.

Study or Subgroup	Experimental Events	Experimental Total	Control Events	Control Total	Weight	Odds Ratio IV, Fixed, 95% CI
1.7.1 Immersive						
Duque 2013	2	30	0	30	3.8%	5.35 [0.25, 116.31]
Gianola 2020	9	44	2	41	14.0%	5.01 [1.01, 24.80]
Jin 2018	0	33	0	33		Not estimable
Subtotal (95% CI)		**107**		**104**	**17.7%**	**5.08 [1.23, 21.01]**
Total events	11		2			
Heterogeneity: Chi² = 0.00, df = 1 (P = 0.97); I² = 0%						
Test for overall effect: Z = 2.25 (P = 0.02)						
1.7.2 Non-immersive						
Anson 2018	3	23	1	21	6.5%	3.00 [0.29, 31.35]
Fu 2015	0	30	0	30		Not estimable
Kwok 2016	3	40	4	40	14.6%	0.73 [0.15, 3.49]
Laver 2012	2	22	0	22	3.7%	5.49 [0.25, 121.18]
Lee 2013	5	32	4	32	17.8%	1.30 [0.31, 5.35]
Monteiro Junior 2015	1	17	3	17	6.3%	0.29 [0.03, 3.13]
Morone 2016	0	19	0	19		Not estimable
Mugueta 2017	0	20	1	20	3.4%	0.32 [0.01, 8.26]
Oesch 2017	11	28	4	26	20.9%	3.56 [0.96, 13.16]
Scwenk 2016	2	11	1	11	5.4%	2.22 [0.17, 28.86]
Tsang 2016	0	39	0	40		Not estimable
Yeilyaprak 2016	3	10	0	11	3.7%	10.73 [0.48, 238.90]
Subtotal (95% CI)		**291**		**289**	**82.3%**	**1.66 [0.86, 3.20]**
Total events	30		18			
Heterogeneity: Chi² = 7.79, df = 8 (P = 0.45); I² = 0%						
Test for overall effect: Z = 1.50 (P = 0.13)						
Total (95% CI)		**398**		**393**	**100.0%**	**2.02 [1.11, 3.67]**
Total events	41		20			
Heterogeneity: Chi² = 9.77, df = 10 (P = 0.46); I² = 0%						
Test for overall effect: Z = 2.31 (P = 0.02)						
Test for subgroup differences: Chi² = 1.98, df = 1 (P = 0.16), I² = 49.4%						

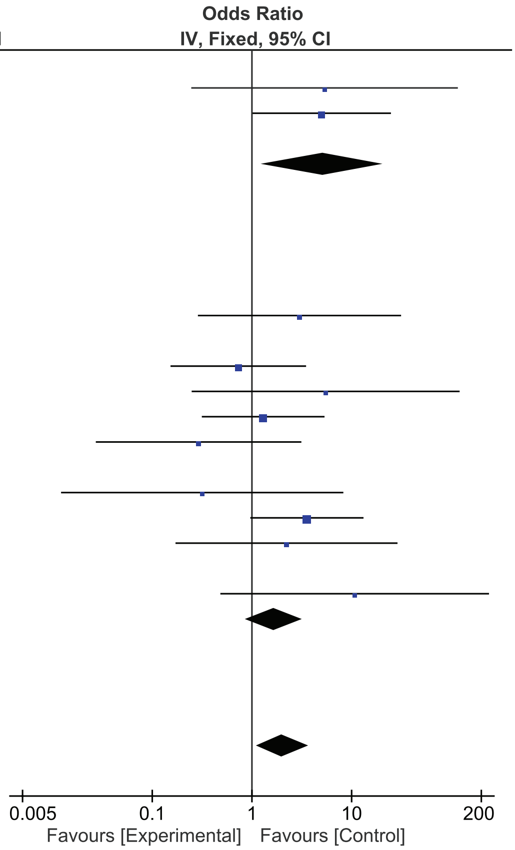

FIGURE 6 | Forest plot of study dropouts.

3.7. Frequency and Classification of Publications With IVR Interventions

To further gain an understanding of the inconsistent use of "VR" as a term to describe technological systems, articles excluded in the full text screening ($n = 163$), were reviewed. After excluding protocols, wrong study design, and "no full text available" articles, the following was extracted from the articles ($n = 108$): information such as intervention description, immersion type, specificity, and availability of software/hardware (commercial or bespoke), the equipment used, and how the authors describe the intervention. Over half om the articles ($n = 60$) used VR to describe the intervention, and three articles used the descriptor "VR" only as a keyword, with no further mention in the paper. Of the 60 articles, 49 (82%) used non-immersive equipment, 10 (17%) used high-immersive equipment (HMD or CAVE systems) and one article did not describe the equipment used in detail, but just referred to "VR-technology" (Cacau et al., 2013), which made classification impossible.

4. DISCUSSION

Virtual rehabilitation continues to evolve as an independent field of study (Keshner et al., 2019). However, despite spanning over two decades, the effectiveness of VR-systems continues to elude, whether specifically made for rehabilitation purposes or adapting recreational non-specific games (Maier et al., 2019). Furthermore, the use of the technology for older adults in non-neurological disorders is still scarce. Even more surprisingly, VR remains a "buzzword" used to describe interventions that do not use IVR-equipment. Both the Oculus Rift CV1 and the HTC Vive were released commercially in early 2016, and the Oculus Rift DK1 was available as early as 2012. Yet, even though VR-systems are now of higher quality and lower prices than previously, IVR-systems appear to be still under-represented in virtual rehabilitation (**Figure 8**). We argue that an increasing public awareness of what *could* constitute a VR-system, paired with a general lack of research consensus on how it should be specifically interpreted and understood, poses a potential health-risk. An example is how the assessment of adverse events are generally under-prioritized in RTCs (Bonell et al., 2015). Our findings affirmed this, as we found adverse events to be generally poorly reported. Although the reporting of no events may be due to a lack of occurrence, it may also be due to only serious events being considered and negligible effects. An example could be how a slight dizziness could easily go unreported. Meanwhile, there is a complexity to adverse effects evaluation, as negligible symptoms may be ignored for (or by) some patient populations,

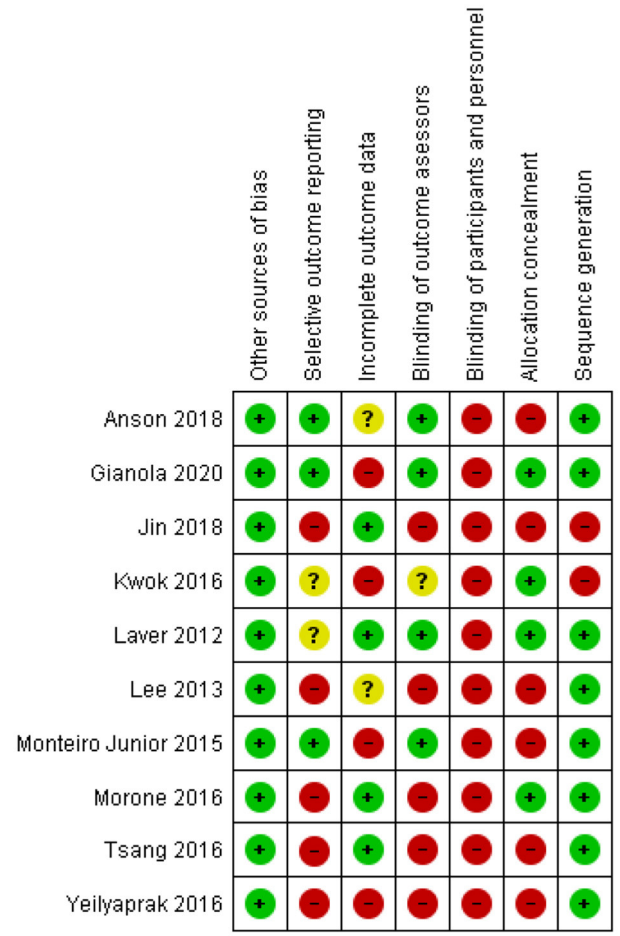

FIGURE 7 | Risk of bias (RoB) summary of included studies (only quantitative synthesis). Icon explanations: green "+",low risk of bias; red "-", high risk of bias; yellow "?", uncertain risk of bias.

while the same symptoms could be considered severe for (or by) others.

Nevertheless, measuring nausea or other VR-related side-effects using standardized tools, is seldom an independent outcome prioritized in randomized trials. However, users experiencing VR-sickness, remains an unsolved challenge which is more frequently observed in IVR-systems (Sharples et al., 2008; Kim et al., 2014; Dennison et al., 2016; Chang et al., 2020). Therefore, if clinical trials are included in syntheses, without accounting for the degree of system immersion, prevalent adverse events may go unnoticed. This has potential harmful human consequences, as national- or international health authorities base their clinical guidelines on these RCT-studies, reviews and meta-analyses, that may not differentiate systems or adverse effects correctly.

The subgroup-analysis between IVR and NVR revealed that the dropout rate for IVR-studies were higher than for NVR-studies. While both tended to have a higher retention for the control group, the dropout rate for IVR experimental groups were significant ($p = 0.02$) while the NVR experimental groups was not ($p = 0.10$). Adverse events were often not properly addressed, except for two studies (Laver et al., 2012; Gianola et al., 2020), who both included a detailed description and discussion. Due to poor reporting we cannot infer causality between dropouts and adverse events. However, description from Gianola et al. (2020) does highlight that dropouts might also be connected to the participants feeling "uncomfortable" wearing the HMD, or lacking face-to-face contact with the therapist. A recent study exploring the acceptance of HMDs among older adults, concluded that attitude changed to positive after experiencing the technology with minimal symptoms. However, there are some caveats related to the authors' conclusion, that negative attitudes or VR-sickness is negligible. Firstly, the results relate to healthy older adults, thus not synonymous and possibly not applicable to more vulnerable users. Secondly, the VR-application used in the experiment (Perfect by nDreams) has the lowest rating on the Oculus comfort spectrum (nDreams, 2016), which implies that related symptoms will be very low. VR content has a significant impact on the amount of symptoms experienced (Saredakis et al., 2020), and symptoms should therefore be evaluated across different content characteristics, before validating a generalized use.

At least one article describes preliminary steps to delimit adverse events (Sobral Monteiro-Junior et al., 2015), but it would be beneficial if adverse events, related to IVR-systems, are measured more consistently with standardized instruments (e.g., the SSQ) in future studies. This would allow to gain a more systematic understanding of the potential challenges with VR as a therapeutic tool across different patient populations, age-groups, and systems.

4.1. Summary of Main Findings

The studies included in this review varied widely across the intervention type and dosage, outcome measures participant characteristics and setting. Participants in the included studies ranged from hospital inpatients, to residential aged care, to people living in the community. This range of settings and focus on different conditions or diagnoses, suggests that participants may be different at baseline, making it difficult to compare. Additionally, all analyses had high heterogeneity, demonstrating large variation across the included studies. While motivation, engagement and adherence are commonly cited as benefits of the use of VR in the therapy setting, only one study evaluated this outcome (Oesch et al., 2017). This seems paradoxical, since motivation is often a central principle in the reasoning for using the technology in the first place.

4.1.1. Taxonomy of Virtual Rehabilitation Systems

Although the intention to classify VR-systems based on level of immersion was pre-specified in the protocol, a *Taxonomy of Virtual Rehabilitation Systems* was developed *a posteriori* to the findings in this review, expand upon the different types of VR-systems, both in terms of *immersion* [non-immersive (NVR) vs. immersive (IVR)] and *specificity* [specific (S) vs. non-specific (NS)] (see **Figure 9**). The latter is describing systems developed exclusively for rehabilitation purposes (specific), as opposed

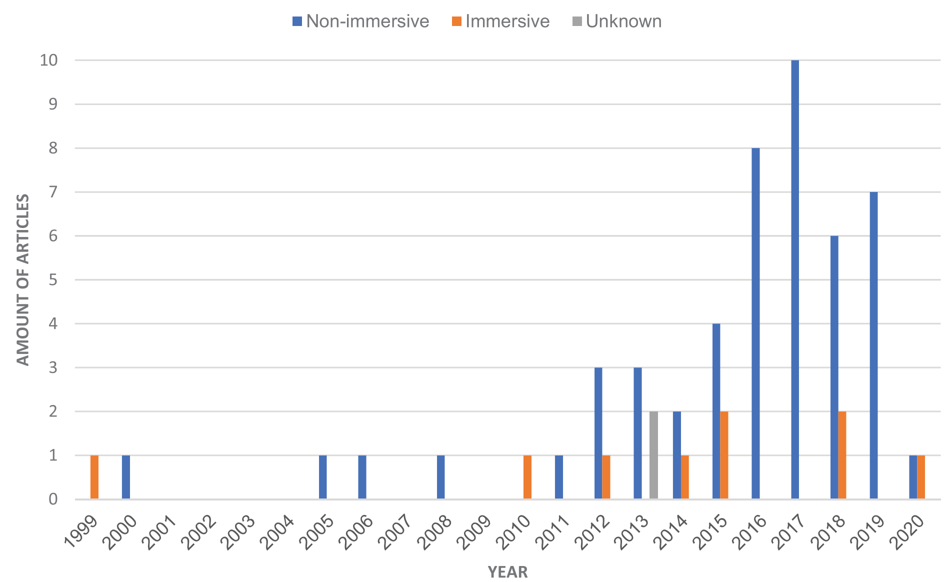

FIGURE 8 | Frequency plot of the articles ($n = 60$), published between 1999 and 2020, which were excluded in the eligibility assessment, who used "Virtual Reality" to refer to the intervention. The graph shows interventions post-classified as immersive or non-immersive, by the authors, according to the taxonomy of virtual rehabilitation systems (see **Figure 9**).

to recreational and/or off-the-shelf video games, which have simply been applied to rehabilitation interventions (non-specific) (Maier et al., 2019). Furthermore, to account for implications for practical applications and availability of the systems, the taxonomy sub-classifies each type of system. Specifically, this depends on whether or not the systems are *commercially* (C) available as a "closed system," or have been developed as *bespoke* (B) technology, which presumably makes it less accessible as an off-the-shelf product.

Non-immersive VR - Non-specific (NVR-NS)

This sub-category most notably entails commercial NVR-NS(C) systems, such as the Nintendo Wii, with studies that are more easily reproducible, due to the consistency and availability of the systems and software. Likewise, the studies are frequently larger, and span a wide spectrum of patient populations. The caveat is that the systems are not developed for the target population, i.e., people with disabilities. Therefore, studies will encounter users who are not able to operate the system, which may introduce frustration and lack of motivation. Bespoke NVR-NS(B) systems within this sub-category will likely be underrepresented. We have not identified any studies using NVR-NS(B) systems.

Non-immersive VR - Specific (NVR-S)

Acknowledging the issues with NS systems, many studies have also utilized specifically designed systems, to tackle some of these problems. Issues with commercial NVR-S(C) systems include that they are often expensive purchases, or requiring renewable licenses. Bespoke NVR-S(B) systems are also frequently represented in the literature, however, are often designed specifically for the study and often not publicly available. Functionalities are sometimes described in great detail, but we argue, mostly not sufficiently, to reproduce and replicate findings.

Immersive VR - Non-specific (IVR-NS)

Similar to what the Nintendo Wii achieved in 2006, VR-headsets are now an affordable and commercial off-the-shelf solution. We therefore anticipate an increase of studies evaluating IVR-NS(C) applications within rehabilitation contexts in the near future. For example, we identified one recent publication with preliminary results (Erhardsson et al., 2020) using the IVR-NS(C) application *Beat Saber* (2018). Other potential IVR-NS(C) applications currently available, could include *Job Simulator* (2016) or *OhShape* (2019). The primary challenge, similar to NVR-NS(C) systems, is how such systems are developed for users with normal function and abilities. Most likely, there will be no specific settings constructed to allow inclusivity toward "extreme users." Bespoke IVR-NS(B) systems for rehabilitation, while unlikely, could in practicality exist.

Immersive VR - Specific (IVR-S)

Commercial IVR-S(C) systems have been available since at least 2010 (Medicaa's Balance Rehabilitation Unit™ (BRU), but as with NVR-S(C) systems, IVR-S(C) systems are often expensive and are likely to require renewable license. More of these will appear, as companies with an already established brand in NVR-S(C) systems, apply "immersive modules" to their existing hardware. We expect them to acknowledge the increasing demand for such systems, for example *Khymeia VRRS®* . Bespoke IVR-S(B) systems will also likely start to appear more frequently, both clinically and within research, which

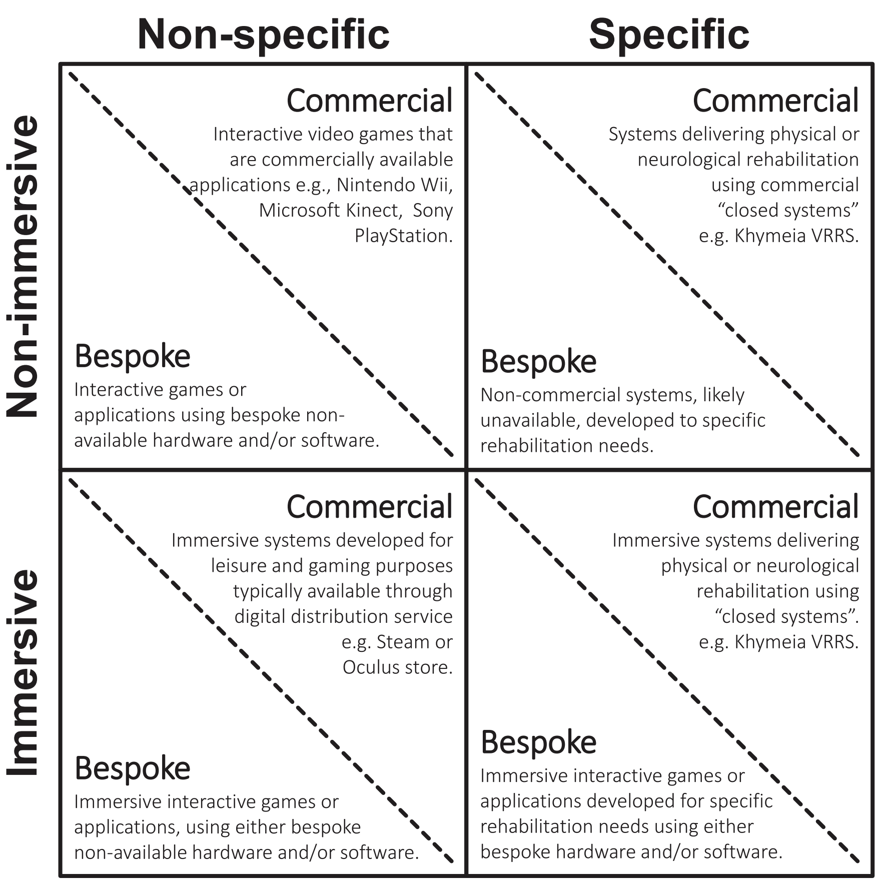

FIGURE 9 | Taxonomy of virtual rehabilitation systems.

will likely create a more balanced representation between NVR and IVR systems. However, we argue that a problem with IVR-S(B), similar to NVR-S(B), is how bespoke systems are rarely commercially available, but developed and maintained in closed research ecosystems. This makes research reproducibility very challenging.

Looking at the applicability of this taxonomy, we see how a bulk of research included in this review, is the adaptation of the NVR-NS(C) classified Nintendo Wii. While disheartening from an IVR review-based needs-perspective, the advantages of the Nintendo Wii's (C) classification are clear as they include *availability, technological reliability*, and *production value*. This infers that working within the (C) classifications, can provide preconditions for studies, resulting in fundamental advantages. These include how studies can prepare quickly, do not face technological inconsistencies, and can be easily and globally reproduced. Whether "NS" is ultimately a serious disadvantage, depends on how well the contextual rehabilitation needs, converge with the demands and effects of the non-specific solution. Noticeably remaining in this case example, is the role of the NVR nature of the Wii.

While IVR is a technology with high potential benefits - typically amplified from the sensation of *presence*), it also entails an increase in risks such as falls or injuries (e.g., from not being aware of ones surroundings, while wearing the headset), to nausea, ocular disturbances, and disorientation, which may be negligible or severe depending on the individual participants. While (B) applications may be aimed to fit contextual needs more precisely, they may also lack the refinement and additional benefits of some (C) grade products.

IVR-NS(C) products are currently undergoing rapidly increasing development, both in terms of quantity and quality. With products such as Beat Saber and Half-Life Alyx breaking records for IVR software sales, IVR-NS(C) titles are gradually demonstrating potential for usage, across entertainment- and clinical settings. These represent a point for IVR, where their success is likely gaining more from effectively utilizing the defining features of IVR to their advantage, than they are losing from any adverse effects. Researchers and practitioners should definitely consider any apprehension, on utilizing (C) products as their vehicle to explore the viability of IVR-based rehabilitation.

This does require researchers to find proper interventions for the IVR-NS(C) applications, and to design their studies around those spaces, where their applications are therapeutically and methodologically useful. Meanwhile, as this was possible for the Nintendo Wii, it should be considered within a range of possibility for current or future IVR applications. We are still to see the IVR-NS(C) application, which achieves weight and role within IVR-based rehabilitation, as the Wii did in the past for NVR-NS(C) based rehabilitation.

Meanwhile, developing this taxonomic classification for VR systems is a starting part of this. If a non-discreet distinction between the non-immersive and immersive exists (on a continuum), the current state of RCT-descriptions of technologies pinpoint a *demarcation problem* of immersion. The taxonomy proposed in this review, is a layer to this. Acknowledging the placement of an intervention is important, especially based on the findings of this review, to make initial judgement on the research field it should be place.

Despite the taxonomy proposed in this review, however, more detailed classification methods remain needed to further distinguish IVR-based interventions. For example, from the usage of FOV and FOR. Currently, information about interventions are seldom sufficient enough, to use those measurements as variables.

4.2. Overall Completeness and Applicability of Evidence

Limited detail about the intervention was provided in the included studies, which limits the ability to replicate the research. This is especially true of specific bespoke systems. When not commercially available, and when details about hardware, software and interactions are not described in detail, bespoke systems become exceedingly difficult to include in cross-study evaluations or comparisons. Future research endeavors should carefully consider and attend to this inclusion.

4.3. Potential Biases in the Review Process

This systematic review verifies and supports previous suggestions in narrative reviews, where the term VR has been used inconsistently, when describing interventions. Furthermore, given that a majority of the articles are published after 2016, which correlates with the availability of high-immersive commercial and affordable VR-equipment, this review supports the need for development and evaluation of more high-quality interventions. Partly to better understand the effectiveness and adverse events of IVR-equipment in motor rehabilitation of older adults, but also in other domains where better evidence exists, such as stroke therapy (Laver et al., 2017).

Many factors contribute to the sense of the immersion (see section 1.2), thus, the dichotomous classification applied in this review is quite reductionistic. Although it can be argued that immersion exists on a continuum, the extent of interacting elements that nurtures it, curtails clear demarcations between the different features. Furthermore, classifying virtual rehabilitation systems a posteriori on a continuum, would require detailed technical descriptions (e.g., FOV, FOR, and frame-rate), which RCT-studies do not traditionally supply.

4.4. Limitations of This Review

To our knowledge, this is the first systematic review attempting to evaluate differences in treatment effects, by differences in the properties of the system, though subgroup analyses. However, the authors acknowledge that there are limitations to this approach. Firstly, the scope of the review spanned a variety of different outcomes, and potentially heterogeneous populations, as long as it was non-neurological rehabilitation. This raises the question about whether the data from independent studies can be validly pooled. One of the criteria for pooling data in meta-analyses, is that treatment effects are investigated for the same fundamental impairments, using similar or identical systems and comparators. While this review does include a very specific population (i.e., older adults), it differs in the purpose of the interventions, as well as the potential functional capacity of the included participants. Likewise, the comparator offered in the control groups differed from being no activity at all, to leaflet and the same exact intervention minus the digital augmentation. Therefore, the substantial heterogeneity observed, for example in TUG ($I^2 =$ 68%), can be due to differences across participants, study design and outcomes, rather than sampling errors. Furthermore, the small number of included studies describing non-neurological IVR-interventions for older adults (60+), the insufficient reported reasons for dropping out, as well as a generally poor description of adverse events, do pose severe limitations. As 56% of studies did not report adverse events, however, we cannot assume there were no adverse events, simply because none were reported. Moreover, since IVR and NVR is usually pooled, safety, and feasibility of the technology may be inflated.

4.5. Future Directions

As VR-systems improve (e.g., wider FOV, higher pixel density, frame-rate, and resolution), the adverse symptoms experienced by many users, will likely be mitigated. However, other challenges may also be relevant to consider, when implementing IVR in rehabilitation programs. Technological innovations will need to be continuously monitored and deemed appropriate for clinical use, as new barriers may arise when new interfaces are inevitably added, as new design standards. For example, mass-market brain-computer interfaces are likely to become embedded in wearable computing devices, within a foreseeable future. Although it definitely will be a game-changer for patient monitorization during therapy, it is not unlikely that such interfaces can be considered in violation with personal data protection regulations, when placed in off-the-shelf commercial products. For researchers seeking to implement clinical VR, it may be valuable to theorize on the potential harms of the technology, and evaluate it continuously during the process. One approach to evaluating the potential harmful consequences, could be through the development of "dark logic models" (Bonell et al., 2015).

In this review we have proposed a taxonomy expanding the previous distinction between *specific* and *non-specific* VR (Maier et al., 2019) to include the distinction between *immersive* and *non-immersive* VR, as well as differentiation between *commercial* and *bespoke* systems. Admittedly, the field of Virtual Rehabilitation has so far used VR as an umbrella-term. However, to avoid confusing consumers, researchers, and healthcare professionals alike, who are leading the change, the recent commercialization of VR should re-establish discussions - and reach a taxonomic consensus on whether (or not) the term of "VR" should be reserved exclusively for IVR-systems, as a subcategory of Virtual Rehabilitation.

Finally, the authors encourage that similar methods are taken, to distinguish between NVR and IVR interventions in more focused reviews, to better understand the differences in treatment effects and related adverse events. Potentially, this task can be undertaken through umbrella reviews, to synthesize results from systematic reviews, while accounting for *a posteriori* classifications.

5. CONCLUSION

The majority of studies included in this review evaluated the use of non-specific, commercially available NVR systems. Three of the 15 studies included in this review evaluated IVR interventions. Two of these studies met the criteria for meta-analysis. Six studies included in the meta-analysis indicated a significant treatment effect of NVR on TUG scores and BBS scores compared to the control intervention. No significant difference in 6MWT scores were found in the meta-analysis of the two studies using NVR interventions. Pain scores were significantly different for the two IVR interventions compared to control for patients, following total knee arthroplasty. Yet, no significant difference was found in pain scores between the NVR interventions and control, for people with chronic back pain or balance disorders.

We initialize a call-for-action, to distinguish between types of VR-technology, and propose a taxonomy of virtual rehabilitation systems, based on our findings. Most interventions uses NVR systems, which has demonstrably lower VR-sickness than IVR-systems. Therefore, RCT adverse events may be under-reported. An increased demand for IVR-systems highlight this challenge. Care should be taken when applying the results of existing NVR tools to new IVR technologies. NVR could improve functional outcomes, and should not be underestimated, simply by to the contemporary existence of IVR. Future studies should provide more detail about their interventions, and future reviews should differentiate between NVR and IVR.

5.1. Implications for Practice

The heterogeneity in VR intervention, participant type, study setting and outcome measures across the included studies, along with small sample sizes, provide limited ability to draw strong conclusions to support the use of VR in practice. Stakeholders and clinicians should be careful when applying the results of existing NVR interventions to new IVR technologies. While both NVR and IVR can effectively improve functional outcomes, IVR generally causes more adverse events, such as VR-sickness which can lead to higher dropout-rates, or even worse pose health-risks if patients are not properly monitored.

5.2. Implications for Research

Future studies should provide more detail about the equipment used in the interventions, and also better monitor, measure and report system-specific side effects through standardized tools. Future reviews should differentiate between NVR and IVR.

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/s.

AUTHOR CONTRIBUTIONS

EH, JB-P, TP, and SF conceived and formulated the research questions for the study. EH drafted the a priori protocol, analyzed the data, and drafted the manuscript. SF and SH performed the literature search, identified and removed duplicate records, and prepared files for Covidence. EH and TP performed title and abstract screening as well as full-text screening, and resolved conflicts between raters. EH, TP, JB-P, KH, and NN performed independent data extraction and Risk of Bias assessment. EH, BL, and JB-P interpreted results of the data synthesis. EH, BL, JB-P, NN, SS, TP, SF, and CK edited and contributed to the manuscript. All authors reviewed and accepted the final 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/frvir.2021.647993/full#supplementary-material

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Immersive Education for Chronic Condition Self-Management

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Chronic conditions represent a significant twenty first century challenge. Education and self-management training are the mainstay of clinical intervention for such conditions since care is dependent on health literacy and self-management. This intervention not only imparts the necessary understanding and skills for self-management, but also helps people to overcome personal barriers to positive behavioral change, such as low self-efficacy. Moreover, education maximizes dignity, by enabling shared decision-making. A plethora of research supports the role of education and self-management training in the management of chronic conditions, whilst at the same time highlighting that not all approaches lead to meaningful behavioral change. Immersive virtual reality (VR) offers a unique set of features and tools for delivering these interventions. For example, the immersive nature focuses attention and promotes engagement; the ability to simulate authentic and interactive real-world scenarios can be used to promote the benefits of active learning; and the ability to facilitate embodiment of avatars with distinct appearance and capability can be used to bias new perceptions and behaviors in-line with the avatar's characteristics. Moreover, the ability to use VR independent of a clinician renders a potential solution to instances where significant barriers to healthcare access exist. This short perspective paper will discuss how VR may be used to host education and self-management interventions in the domain of chronic condition management. Further, it will outline considerations for developers and conclude with a call for the co-creation of new VR-based education and self-management interventions.

Keywords: virtual reality, chronic condition, chronic disease, self-management, health education (MeSH)

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INTRODUCTION

Rationale

Chronic conditions are responsible for a significant burden on both individuals and society. Globally, 38 million people die from these conditions annually, while their economic burden is projected to reach USD$7 trillion by 2025 (World Health Organization, 2014). While medical treatments have advanced, most chronic conditions depend on long-term adherence to self-management strategies—typically requiring behavioral changes involving diet, rehabilitation and exercise, the correct use of prescription medications, and mitigation or elimination of risk factors such as smoking and stress (Allegrante et al., 2019). As a result, the development of interventions that can assist people in adopting and maintaining long-term self-management has significant potential for impact. Education and skills training are the mainstay of such management.

Virtual reality (VR) has been considered one of the most promising tools to promote learning in educational and workplace training contexts (Liu et al., 2017a), and hence there is much to gain from considering its potential role in providing education to people with chronic conditions. VR is a simulated experience that can be similar to, or completely different from, the real world. In immersive VR, an artificial reality is presented to the user via a Head Mounted Display (HMD), such that the user voluntarily suspends belief and accepts the digitally presented scenario. Immersive VR has been used as a medium for chronic condition interventions such as exposure therapy for phobias and post-traumatic stress, kinesthetic training for chronic neck pain, and physical rehabilitation (Gohari et al., 2019). Whilst immersive VR has been used to deliver information about the science and psychology of pain, as well as in teaching relaxation and mindfulness skills to people with chronic pain (Louw et al., 2019; Darnall et al., 2020), its application in delivering self-management programs is not yet common. Developing such interventions using this new platform is likely complex, and consideration is needed regarding how to assimilate: (1) The unique tools afforded by immersive technologies, (2) The education and training needs of people with chronic conditions, and (3) The key theoretical models that describe the underpinnings of learning and behavior change. These three domains will be now be discussed in more detail.

UNIQUE FEATURES OF VIRTUAL REALITY FOR EDUCATION & TRAINING

Studies show that simply porting computer-based interventions into VR does not necessarily improve learning, and may even have a negative impact. For example, one study compared a computer-based biology lab simulation to the same class ported directly to VR. The result was a reduction, rather than improvement, in learning outcomes (Makransky et al., 2019). In contrast, another study compared a computer-based trauma response training program to a VR training equivalent built with the features of immersive VR in mind (Coulter et al., 2007). The result was a significant improvement in learning outcomes. Thus, consideration of the unique features of VR and how they may intersect with the goal of learning (and behavior change) is likely to be essential to creating effective interventions.

Attentional Focus: Immersion, Presence, Engagement

The quality of immersion refers to the level of sensory fidelity provided by a VR system hardware and software. Presence is the subjective perception of being physically present in a non-physical world (Slater, 2003, 2018). As such, a system that is more immersive, results in greater illusory presence. With this sense of presence comes engrossment in the multisensory experience, and an exclusion of other internal and external stimuli. This intense attentional focus has been exploited by clinician's seeking temporary pain and anxiety relief during medical procedures (Chan et al., 2018; Eijlers et al., 2019). Importantly, learning depends on directing one's attention toward, and engaging with, educational content (Kolb, 1984). As such, one would predict that this immersive feature would result in better learning outcomes. However, increasing attentional focus in VR does not necessarily translate to learning performance, and paradoxically may reduce it—perhaps by over-loading cognitive resources (Krassmann et al., 2020). As such, self-management related educational content in VR should not rely on this feature alone to improve learning. Moreover, driving development resources into optimizing immersion may yield diminishing returns. Rather, developers should look to optimize other aspects of VR education and self-management training.

Interaction and Role Play

From a young age, learning is linked with movement. According to some learning scientists, the use of movement and gesture helps to off-load mental work and free cognitive resources for consolidation of learning (Goldin-Meadow, 2011). Moreover, it may aid in maintaining motivation and engagement with the educational content. By mapping real-world movement to virtual movement, interactive VR enables users to change their visual perspective, and to manipulate virtual objects using virtual hands. Combined with the ability to simulate both real and abstract scenarios, VR affords unmatched potential to create life-like interactive learning scenarios. These scenarios may relate to understanding their condition or management principles, rehearsing lifestyle or disease management skills, or overcoming personal or social barriers.

Embodiment

In VR, a digital avatar can be substituted for the participants real body and displayed from a first-person perspective. Moreover, virtual and real movement can be tethered. This visuomotor congruence results in the illusory "embodiment" of the digital avatar (Slater et al., 2010; Serino et al., 2016). This illusory ownership over a virtual body supports the sense of presence in the virtual world and may be leveraged to support the learning outcomes. That is, developers can manipulate the characteristics of the avatar to have certain capabilities in a way that biases certain perceptions or behaviors. This technique, along with example applications in the domain of chronic condition management, will be discussed further in sections related to embodied learning and the Proteus effect.

Practical Aspects

For many people with chronic conditions, access to multidisciplinary face-to-face interventions that promote self-management may be limited. This lack of access may result from geography and the lack of appropriately trained clinicians, or limitations related to disability, transportation, time, or finances. Limitations also extend to clinician time which is often focussed on immediate needs or biomedical aspects of a health condition, rather than patient empowerment. Digital health interventions can assist to overcome these structural barriers. In addition, they may also assist in overcoming individual and social access barriers. For example, cultural norms and stigma may prevent some patients seeking assistance from therapists such as psychologists and dieticians. Accessing, for example, stress management or behavioral nutrition training in VR may bypass this barrier, particularly if it is couched within a broader biopsychosocial intervention.

A fact of VR that is rapidly increasing its feasibility, is its diminishing cost and increasing portability. For example, the Oculus Quest costs USD$299 and does not require a separate computer to operate. As such, it is possible to post it out to clients, for example as part of a telehealth intervention. These practical features of VR should not be underestimated and give meaningful direction to where the technology may be best placed.

CHRONIC CONDITION EDUCATION AND TRAINING NEEDS

Historical Perspective

The historical biomedical approach to healthcare involved training practitioners to treat conditions, without close consideration of the psychosocial context (Allegrante et al., 2019). Factors such as the individual's knowledge, motivation, capacity and resources for carrying out the necessary action were not prioritized (Allegrante et al., 2019). Over the years, chronic condition education has evolved from a compliance-oriented approach, toward an empowerment- and self-management-oriented approach (Allegrante et al., 2019). Whilst health knowledge correlates with outcomes (Camerini et al., 2012), improvements in health behaviors are greater when education is combined with empowerment and self-management training (Allegrante et al., 2019). While these interventions show consistent efficacy, their benefit is often modest, suggesting scope for improvement (Allegrante et al., 2019; Safari et al., 2020) (Hermanns et al., 2020).

The Insufficiency of Knowledge

As mentioned, knowledge acquisition is often insufficient to improve self-management (Ockene et al., 2002). That is, knowledge does not directly translate to new health behaviors unless coupled with: an intention to change, a belief that one has the capacity to change, and the skills to action that change. In this light, VR training programs for chronic conditions should be developed with close attention to learning and behavior change models, such as the Theory of Planned Behavior (Ajzen, 1991). Notably, individual models of behavior change have significant limitations (Rich et al., 2015), and considering additional models such as the PRIME Theory of Human Motivation (West and Brown, 2013), may yield additional insight for development.

Beliefs, Attitudes, Motivations

Knowledge acquisition is impotent if it does not alter beliefs. Likewise, altering a belief is impotent without altering attitude toward a behavior and provoking an intention to change. As such, information must be not only informative, but persuasive. It may be useful to view intention to change along a spectrum, where the central point is a state of ambivalence—characterized by inaction underpinned by unresolved internal ideas about change. Motivational techniques can aid in resolving ambivalence by highlighting personal motivations for change (as well as motivations for inaction) (Engle and Arkowitz, 2006). In VR, engaging, highly visual, and interactive tasks that highlight the benefits of change. Inspiration for such experiences may be drawn from other fields. For example, VR has been used to motivate change in perpetrators of domestic violence, by virtually placing them in the role of victim (Ventura et al., 2020). Salient experiences highlighting the consequences (non)change, and aim to resolve ambivalence, may be one motivation-based application of VR in chronic disease management. Similar non-VR techniques normally facilitated by a clinician are known to aid resolution of ambivalence (Engle and Arkowitz, 2006). Moreover, VR offers ways to facilitate such a task remotely and with the application of principles of learning and behavior change discussed elsewhere in this paper.

Changing Perceptions

Unhelpful social stigmas and perceptions about health and chronic condition management pervade the public sphere (e.g., Louw et al., 2019; Pandrangi et al., 2019; Halabi, 2020; Jung et al., 2020). For example, the belief that health is something managed by health care providers and not something that must be self-managed is still widespread. This aspect is referred to as the subjective norm in the Theory of Planned Behavior (Ajzen, 1991). As such, interventions aiming to improve self-management should consider addressing these perceptions and extol the benefits of patient-led care. Perceptions about management can also be augmented through positive peer support and modeling. The inclusion of a social element within a VR intervention is currently challenging, although Multiple User Virtual Environments have been used (Pillen et al., 2020).

Self-Efficacy: Improving Perceived Control

According to the Theory of Planned Behavior, any intention to change must be complimented by: 1. The perception that one can change, and 2. The actual skills needed to execute the new behavior(s) (Ajzen, 1991). Here, perceptions are a focus, because adopting new self-management behaviors requires patients to accept that improved health is within their power (locus of control) and that they have the capacity (self-efficacy) to execute the necessary change. As such, educational self-management interventions should seek to directly target perceptions of control. With well-designed applications, VR is well-placed to assist in this way. Here, rehearsal of new skills in realistic simulations and with the provision of positive feedback, a user is likely to build a sense of agency and control through experience.

Self-Efficacy: Improving Actual Control

The type of skill building required for effective chronic condition management or rehabilitation will be specific to that condition. For example, the skills required to manage chronic pain may include pacing and graded activity skills; stress-management techniques such as cognitive diffusion or meditation; problem-solving and goal-setting skills; and sleep management schemes. Managing diabetes on the other hand, may focus skills related to weight loss such as meal planning and blood glucose monitoring. Such skills may be acquired and rehearsed in interactive VR scenarios, and made effective through the implementation of gamification, task progression, feedback and reward schemes.

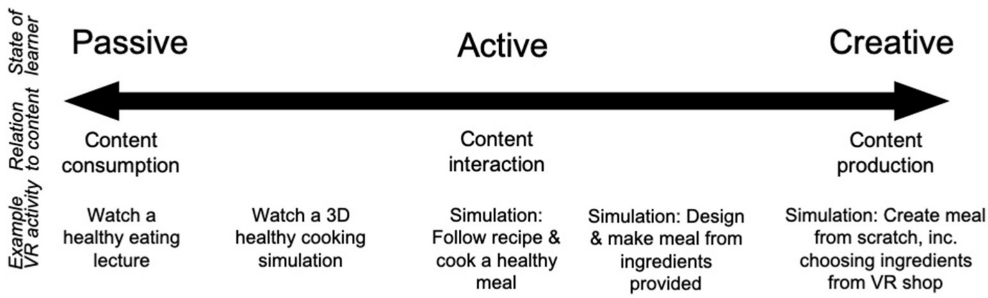

FIGURE 1 | A scale of relating to the learning theory of constructivism.

One example of a simple implementation of skills training in VR for chronic pain is relaxation training for stress management (Darnall et al., 2020). Here, training to self-induce a relaxed state can be made easier by overlaying relaxing audio-visual contexts and breath detection and feedback techniques (Darnall et al., 2020). Notably, such interventions may have implications beyond improving perceived capacity to manage stress. That is, meditation has also been shown to impact cognitive control (Waller and Bates, 1992). Cognitive control refers to our ability to inhibit automatic responses. Cognitive control relates to skills needed when attempting behavior change, such as self-discipline and ability to delay gratification (Waller and Bates, 1992; O'hea et al., 2005).

THEORETICAL MODELS OF LEARNING AND BEHAVIOR CHANGE IN VR

The interplay between learning theory and the affordances of VR have been thoroughly reviewed (Pillen et al., 2020). Here we consider key aspects of learning theory in the context of VR-based education and training interventions for chronic conditions and the specific goal of positive behavior change. As suggested by the Theory of Planned Behavior, the targets of behavior change interventions should consider beliefs and attitudes, perceptions about best and normal care, perceptions of self-efficacy, and skills-based knowledge (Ajzen, 1991). Understanding learning theory represents an opportunity for developers seeking to create effective intervention.

Constructivism

Constructivism is an empirically supported theory where understanding is constructed actively through experiences, and reflections on those experiences (Petrie et al., 1995). The VR toolkit includes features that give it distinct capacity to mediate salient experiences where participants learn through interacting with content, and in a way that either intentionally or naturally stimulates reflection. These features include the ability to simulate abstract scenarios, to simulate numerous real-world scenarios without having to change locations or use physical equipment, the ability to provide real-time feedback, reinforcement and reflective prompts, to apply gamification, and to induce a state of presence that may foster greater engagement and curiosity (Liu et al., 2017b). Constructivist principles are best satisfied in content creation when the participant has greater capacity to constructs his or her own learning experience within the learning environment (Colzato et al., 2015; Pillen et al., 2020). That is, the degree to which constructivist principles are satisfied, can be visualized on a scale of passive consumption of information, through to producers of information (see **Figure 1**, including example VR activities).

Embodied Cognition and Embodied Learning

Embodied cognition is a theory of cognition based on the premise that the brain and body are intrinsically coupled by virtue of their co-evolution (Fox, 2001; Inzlicht et al., 2015). In this theory which supports the constructivist paradigm, the body—along with its sensorimotor capabilities and brain-held representations—provide the neural architecture for human cognitive processes. Health education programs are typically mentalistic—learners sit, watch, and listen, with little engagement of the body. Like other cognitive processes, learning co-evolved with the body. As a result, better engagement of sensorimotor systems in learning has significant potential to enhance education. To this aim, the potential for engagement of the body through interaction, gives VR unique capacity to employ embodied learning principles in a manner that is more scalable than real-world simulated learning.

Narrative-Based Learning

Narrative-based learning is a learning model grounded in the theory that humans define their experiences within the context of narratives—which serve as cognitive structures and a means of communication, as well as aiding people in framing and understanding their perceptions of the world (Fox, 2001). Narrative is also an important motivational component of learning. At the core of the narrative learning approach, is a problem that must be solved by constructing and applying knowledge.

The Proteus Effect

Remarkably, the occupant of a virtual avatar can express new behaviors and attitudes reflective of the character of the avatar (Mahon, 2015; Jacobson, 2017). For example, after flying above

TABLE 1 | Key points for developing education and self-management interventions in virtual reality.

Transdisciplinary team members may include:
- Domain-relevant health professionals and health scientists
- Educationalists
- Behavioral psychologists/behavior change experts
- Narrative designers
- Health communication experts
- End users and funding partners
- Experts in gamification and human-computer interaction
- Content developers, visual and sound designers, programmers

Content of interventions should include strategies to target domains such as:
- Attitudes toward health-related behaviors
- Beliefs that said behaviors are normative/socially desirable
- Perceptions of control
- Skills/actual behavioral control

Environmental and avatar considerations:
- Authenticity of the environment should be optimized to best simulate real-world scenario and/or facilitate presence and engagement
- The nature and capabilities of the virtual body could be considered where it may be desirable to leverage the Proteus effect

Prioritize active, embodied, narrative learning:
- More movement and interaction are better than less
- Movement/gestures should be meaningful where possible
- Greater user choice and opportunities for creativity is best
- Experiences that are guided, rather than structured are optimal
- Use of narrative contextualizes content and frames understanding
- Gamification principles aid engagement and reinforce learning
- Producing content and creative interactions are optimal

Importance of generalization:
- Strategies to aid generalization of learning to real-world outcomes should be considered. This may include a transfer phase, where content is reflected upon or rehearsed in the real-world

Feedback and evidence:
- Seek and respond to end-user feedback throughout process
- Form research partnerships and undertake formal clinical testing as early as possible

a virtual city as a superhero, participants are more likely to help an experimenter pick up a jar of "accidentally" spilled pens than if they flew in a virtual helicopter (Ziemke, 2016). Participants have even been shown to perform better on cognitive tasks when embodying Einstein (Bruner, 1991). This close relationship between mind and (perceived) body has been described as embodied cognition (Fox, 2001; Inzlicht et al., 2015). One recent clinical application of this idea was in a case report with a person with Chronic low back pain (LBP) (Slater and Sanchez-Vives, 2014). Here, the patient's presentation included negative body-related attitudes and perceptions, such as low physical self-confidence and perceptions of physical vulnerability that may have contributed to his presentation and level of disability. When the patient embodied avatars that had high-physical capability and athletic physical-appearance, the patient displayed more positive self-perceptions—such as greater perceptions of strength and confidence with physical activity.

Generalization

The concept of generalization is well-known in the learning sciences (Slater, 2017). Generalization denotes that learning in one context, does not necessarily fully translate to another context (Rosenberg et al., 2013; Slater, 2017). As such, VR education programs should consider intermediate steps to facilitate real-world translation. In the case of VR relaxation training for example, a "transfer phase" could be included that introduces relaxation techniques into real-world routines. Transfer may also be aided by a debriefing session, between the clinician and client, following the simulation.

Examples From the Literature

While existing examples in the literature are scant, most do not capitalize on the features of virtual reality or leverage education science principles**.** For example, a recent VR-based education and rehabilitation for chronic lung disease delivered education simply as 2D videos in a 3D environment (Banakou et al., 2018). Others use 3D content simply to view anatomical pathology, and aid understanding of a disease state (e.g., Harvie et al., 2020). Some applications have used experiential learning techniques. For example, one application uses a virtual lion to induce fear—presumably to show how our defensive response systems (e.g., fear and pain) respond to the perception of danger, rather than danger itself. This is likely to persuade patients that their pain is not necessarily a sign of damage, and that re-engaging in activity is safe (Banich and Caccamise, 2011). Moreover, meditation-based games that interact with the user's breath, have been used in applications that teach stress-management skills (Darnall et al., 2020). Educational techniques that align with the imaginative and creative mandate of the constructivist paradigm are difficult to find in the health context but may be found elsewhere (e.g., Sharkey and Sharkey, 1993).

CONCLUSION

Immersive VR has opened up a world of possibilities in healthcare and beyond, most of which are currently untapped. Whilst not exhaustive, this review has described many of the important features of VR that make it a potentially transformative tool for facilitating education and self-management interventions for people with chronic conditions. Moreover, it has outlined some of the key learning theories that intersect with the features of VR that may assist in effective program development (see **Table 1** for a summary table of key points for developing education and self-management interventions in VR). While developer tools such as visual scripting and large repositories of pre-modeled assets reduce the resources and time required to develop new applications, the effort needed to create high-quality experiences should not be underestimated. Indeed, the effectiveness of a VR intervention will rely on the design and production quality, as much as the educational content itself. As such, progress in this space will require support from funders of health research and industry, as well as transdisciplinary collaboration. This co-design process may include: (1) Narrative designers, specialized health communication experts and educationalists, (2) Health and behavioral psychology experts from academic, clinician and patient perspectives, (3) Visual and sound content developers and software programmers, and 4. Experts in human computer interaction and gamification. Key points for developing education and self-management strategies are summarized in **Table 1**. Given the potential upside of improved self-management in the growing problem of chronic conditions, leveraging tools with strong potential is imperative.

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Comparison of Dexterous Task Performance in Virtual Reality and Real-World Environments

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Virtual reality is being used to aid in prototyping of advanced limb prostheses with anthropomorphic behavior and user training. A virtual version of a prosthesis and testing environment can be programmed to mimic the appearance and interactions of its real-world counterpart, but little is understood about how task selection and object design impact user performance in virtual reality and how it translates to real-world performance. To bridge this knowledge gap, we performed a study in which able-bodied individuals manipulated a virtual prosthesis and later a real-world version to complete eight activities of daily living. We examined subjects' ability to complete the activities, how long it took to complete the tasks, and number of attempts to complete each task in the two environments. A notable result is that subjects were unable to complete tasks in virtual reality that involved manipulating small objects and objects flush with the table, but were able to complete those tasks in the real world. The results of this study suggest that standardization of virtual task environment design may lead to more accurate simulation of real-world performance.

Keywords: activities of daily living, performance metrics, virtual task environment, upper limb prosthesis, functional performance

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INTRODUCTION

It was estimated in 2005 that there were two million amputees in the United States, and this number was expected to double by 2050 (Ziegler-Graham et al., 2008; McGimpsey and Bradford, 2017). The prosthesis rejection rate for upper limb (UL) amputees has been reported to be as high as 40% (Biddiss E. A. and Chau T. T., 2007). Among the reasons for prosthesis rejection is difficultly when attempting to use the prosthesis to complete activities of daily living (ADLs), such as grooming and dressing (Biddiss E. and Chau T., 2007). The prosthesis control scheme plays an important role in object manipulation, preventing objects from slipping out of or being crushed in a prosthetic hand. Improving the response time of the device, the control scheme (i.e., body-powered vs. myoelectric control), and how the device signal is recorded (external vs. implanted electrodes) will help with ensuring that amputees can complete ADLs with less difficulty (Harada et al., 2010; Belter et al., 2013). Programs such as the Defense Advanced Research Projects Agency (DARPA) Hand Proprioceptive and Touch Interfaces (HAPTIX) program have been investigating how to improve UL prosthesis designs (Miranda et al., 2015).

Building advanced prostheses is expensive and time consuming (Hoshigawa et al., 2015; Zuniga et al., 2015), requiring customization for each individual and integration of advanced sensors and robotics (Biddiss et al., 2007; van der Riet et al., 2013; Hofmann et al., 2016). To efficiently study advanced UL prostheses in a well-controlled environment prior to physical prototyping, a virtual version can be used (Armiger et al., 2011). The virtual version can be programmed and calibrated in a manner similar to a physical prosthesis and can be used to allow amputees to practice device control schemes with simulated objects (Pons et al., 2005; Lambrecht et al., 2011; Resnik et al., 2011; Kluger et al., 2019).

Virtual reality (VR) has also been used to aid in clinical prosthesis training and rehabilitation. A prosthetist can load a virtual version of an amputee's prosthesis to allow him/her to practice using the control scheme of the prosthesis (e.g., muscle contractions for a myoelectric device or foot movements for inertial measurement units) (Lambrecht et al., 2011; Resnik et al., 2012; Blana et al., 2016). A variety of VR platforms exist for this purpose, but there is a gap in the literature about what tasks and object characteristics need to be replicated in VR to predict real world (RW) performance. A better understanding of how to design and translate results from VR to RW is needed to inform clinical practice. This paper presents a study comparing performance of virtual ADLs with a virtual prosthesis with RW ADL using a physical prosthesis. We examined what factors affect performance in VR to determine if these factors translate to RW performance. This work will inform the design of VR ADLs for training and transfer to RW performance.

BACKGROUND

Clinical Outcome Assessments

Clinical outcome assessments (COAs) are used to evaluate an individual's progress through training or rehabilitation with their prosthetic device. Research has shown that motor control learning is highly activity specific (Latash, 1996; Giboin et al., 2015; van Dijk et al., 2016); therefore, selecting training activities is important to help a new prosthesis user return to a normal routine. However, few COAs have been developed to assess upper limb prosthesis rehabilitation progress; therefore, activities for assessing function with other medical conditions, such as stroke or traumatic brain injury (TBI), are used (Wang et al., 2018). One such test is the Box and Blocks Test (BBT) (Mathiowetz et al., 1985; Lin et al., 2010), in which subjects complete a simple activity that is not truly reflective of an activity that a prosthesis user would perform in daily life. The goal of the BBT is to move as many blocks as possible from one side of a box over a partition to the other side in 60 s. Researchers have made modifications to the BBT to assess an individual's ability to perform basic movements with their prosthesis (Hebert and Lewicke, 2012; Hebert et al., 2014; Kontson et al., 2017).

Another clinical outcome assessment that has been used to assess UL prosthetic devices is the Jebsen–Taylor Hand Function Test (JTHFT). The JTHFT is a series of standardized activities designed to assess an individual's ability to complete ADLs following a stroke, TBI, or hand surgery (Sears and Chung, 2010). The seven activities in the JTHFT are simulated feeding, simulated page turning, stacking checkers, writing, picking up large objects, picking up large heavy objects, and picking up small objects. Individuals are timed as they complete each activity, and their results are compared with normative data (Sears and Chung, 2010). Studies have been performed with the UL amputee population to validate the use of the JTHFT as a tool to assess prosthetic device performance (Wang et al., 2018). This assessment's use of simulated ADLs makes it a better candidate than the BBT for assessing how a person would use a prosthesis in daily life.

Research has also been performed to develop COAs specifically to assess upper limb prosthesis rehabilitation progress. The Activities Measure for Upper Limb Amputees (AM-ULA) (Resnik et al., 2013) and Capacity Assessment of Prosthetic Performance for the Upper Limb (CAPPFUL) (Kearns et al., 2018) were designed to test an amputee's ability to complete ADLs with their device. These two COAs consist of 18 and 11 ADLs, respectively, and assess a person's ability to complete the activity, time to completion, and movement quality.

While these activities can be completed with a physical prosthetic device, training in a virtual environment has shown to be an effective way to train amputees to use their device (Phelan et al., 2015; Nakamura et al., 2017; Perry et al., 2018; Nissler et al., 2019). Training in a virtual environment can be a cost effective way for clinics to perform rehabilitation (Phelan et al., 2015; Nakamura et al., 2017) and help prosthesis users learn how to manipulate their device using its particular control scheme (Blana et al., 2016; Woodward and Hargrove, 2018), and gamifying rehabilitation has been shown to increase a prosthesis user's desire to complete the program (Prahm et al., 2017, 2018).

Virtual Reality Prosthesis Testing and Training Environments

Several VR testbeds have been created or adapted to evaluate different aspects of prosthesis development. The Musculoskeletal Modeling Software (MSMS) was originally developed to aid with musculoskeletal modeling (Davoodi et al., 2004), but was later adapted for training, development, and modeling of neural prosthesis control (Davoodi and Loeb, 2011). The Hybrid Augmented Reality Multimodal Operation Neural Integration Environment (HARMONIE) was developed to support the study of human assistive robotics and prosthesis operations (Katyal et al., 2013). Users that interact with the HARMONIE system control their device through surface electromyography (sEMG), neural interfaces (EEG), or other control signals (Katyal et al., 2013, 2014; McMullen et al., 2014; Ivorra et al., 2018). Another tool, Multi-Joint dynamics with Contact (MuJoCo), is a physics engine that was originally designed to facilitate research and development in robotics, biomechanics, graphics, and animation (Todorov et al., 2012). MuJoCo HAPTIX was created to model contacts and provide sensory feedback to the user through the VR environment (Kumar and Todorov, 2015). Studies are being performed to improve the contact forces applied to objects in MuJoCo HAPTIX (Kim and Park, 2016; Lim et al., 2019; Odette and Fu, 2019). These testbeds aid in training and studying of prosthesis control in VR, but little is known about how VR object characteristics impact performance.

User Performance Assessment

Simulations should require visual and cognitive resources similar to those needed to complete the activity in the real world (Stone, 2001; Gamberini, 2004; Stickel et al., 2010). While previous studies evaluated VR testbeds or activities implemented in them (Carruthers, 2008; Cornwell et al., 2012; Blana et al., 2016), none have identified the characteristics of the tasks that make an activity easy or difficult to complete in VR. Subjects in these studies did not complete ADLs from COAs that have been validated with a UL population, which could limit the ability to replicate and retest these tasks for RW study.

Study Objectives

The purpose of this study is to provide preliminary validation for a VR system to test advanced prostheses through comparison with similar RW activity outcomes. In addition, this study aims to gain a better understanding of how activity design affects an individual's ability to complete virtual activities with a virtual prosthetic hand. The activities used in this study are derived from existing, validated UL prosthesis outcome measures that are used to evaluate prosthesis control. Motion capture hardware and software were used to collect normative data from able-bodied individuals to determine how activity selection and virtual design affects the completion rate, completion time, and number of attempts to complete the activity. By replicating validated outcome measures in VR, the results from the VR performance was then compared with RW task performance to assess how VR performance translates to RW performance.

METHODS

Task Development

MuJoCo HAPTIX (Roboti, Seattle, Washington) is a VR simulator that has been adapted to the needs of the DARPA HAPTIX program by adding an interactive graphical user interface (GUI) and integrating real-time motion capture to control a virtual hand's placement in space (Kumar and Todorov, 2015) (**Figure 1**). MuJoCo is open source and can be used to test other limb models as well. Four tasks were designed in the MuJoCo HAPTIX environment to study movement quality: (1) hand pose matching, (2) stimulation identification and use of proprioceptive feedback and (3) sensory feedback to identify characteristics of an object, and (4) object manipulation. This research focuses on the MuJoCo object manipulation task, which is based on existing COAs, the JTHFT and the AM-ULA.

Task Selection and Analysis

Eight ADLs from the AM-ULA (Resnik et al., 2013) and JHFT (Sears and Chung, 2010) were completed in VR and in RW (**Figure 2** and **Table 1**). The tasks selected for replication from the JHFT and AM-ULA were chosen for their capacity to assess both prosthesis dexterity and representative ADLs such as food preparation and common object interaction. The moving cylinders (Move Cyl.) task is representative of activities that require subjects to move a relatively large object. The place sphere in cup (Sphere cup), lock/key (Lock Key), and stack checkers (Checkers) tasks are representative of activities that require precise manual manipulation to move a small object. The spoon transfer (Spoon Tran.) and writing tasks required rotation and precise targeting. Research has shown that tasks requiring small objects to be manipulated require more dexterous movement, while tasks where large objects are manipulated require more power and less dexterity (Park and Cheong, 2010; Zheng et al., 2011).

A hierarchical task analysis (HTA) was performed on each of the ADLs to understand what steps or subtasks need to be completed in order to complete the ADL high-level goals. An HTA is a process used by human factor engineers to decompose a task into subtasks necessary for completion, which can help to identify use difficulty or use failure for product users (Patrick et al., 2000; Salvendy, 2012; Hignett et al., 2019). The HTA used for this research focused on the observable physical actions that a person must complete. To ensure that the number of steps presented in the HTA provided sufficient depth for understanding necessary components of the tasks, the instructions for the AM-ULA and the JHFT were referenced to inform the ADL subtask decomposition.

The descriptions of the subtasks utilized seven action verbs: reach, grasp, pick up, place, release, move, and rotate (**Supplementary Table 1**). These action verbs were picked due to their use in describing the steps to complete tasks in the AM-ULA (Resnik et al., 2013). Reach consists of moving the hand toward an object by extension of the elbow and protraction of the shoulder. Grasp involves flexion of the fingers of the hand around an object. Pick up includes flexion of the shoulder and potentially the elbow to lift the object from the table. Move consists of medial or lateral rotation of the arm to align the primary object toward a secondary object or shifting the hand away from one object and aligning it with another. Place involves extension of the elbow to lower the object onto its target. Release involves extension of the fingers to let go of the object. Rotation consists of pronation or supination of the arm to rotate an object.

Subjects

Able-bodied individuals were recruited for this study due to limited availability of upper limb amputees. Prior studies have used able-bodied individuals, with the use of a bypass or simulator prosthesis, to assess the ability to complete COAs and ADLs with different prosthesis control schemes (Haverkate et al., 2016; Bloomer et al., 2018). These studies showed that the use of able-bodied subjects allows the experimenter to control for levels of experience with a prosthetic device and that performance between the able-bodied group and amputee group is comparable.

Twenty-two individuals (10 females, average age of all subjects 35 $\pm$ 17 years) completed the VR experiments, and 22 individuals (eight females, average age of all subjects 38 $\pm$ 16 years) completed the RW experiments. The VR experiment was completed first, followed by the RW experiment to provide a comparative evaluation of virtual task performance and its utility

FIGURE 1 | The virtual environment, Multi-Joint dynamics with Contact (MuJoCo) Hand Proprioceptive, and Touch Interfaces (HAPTIX).

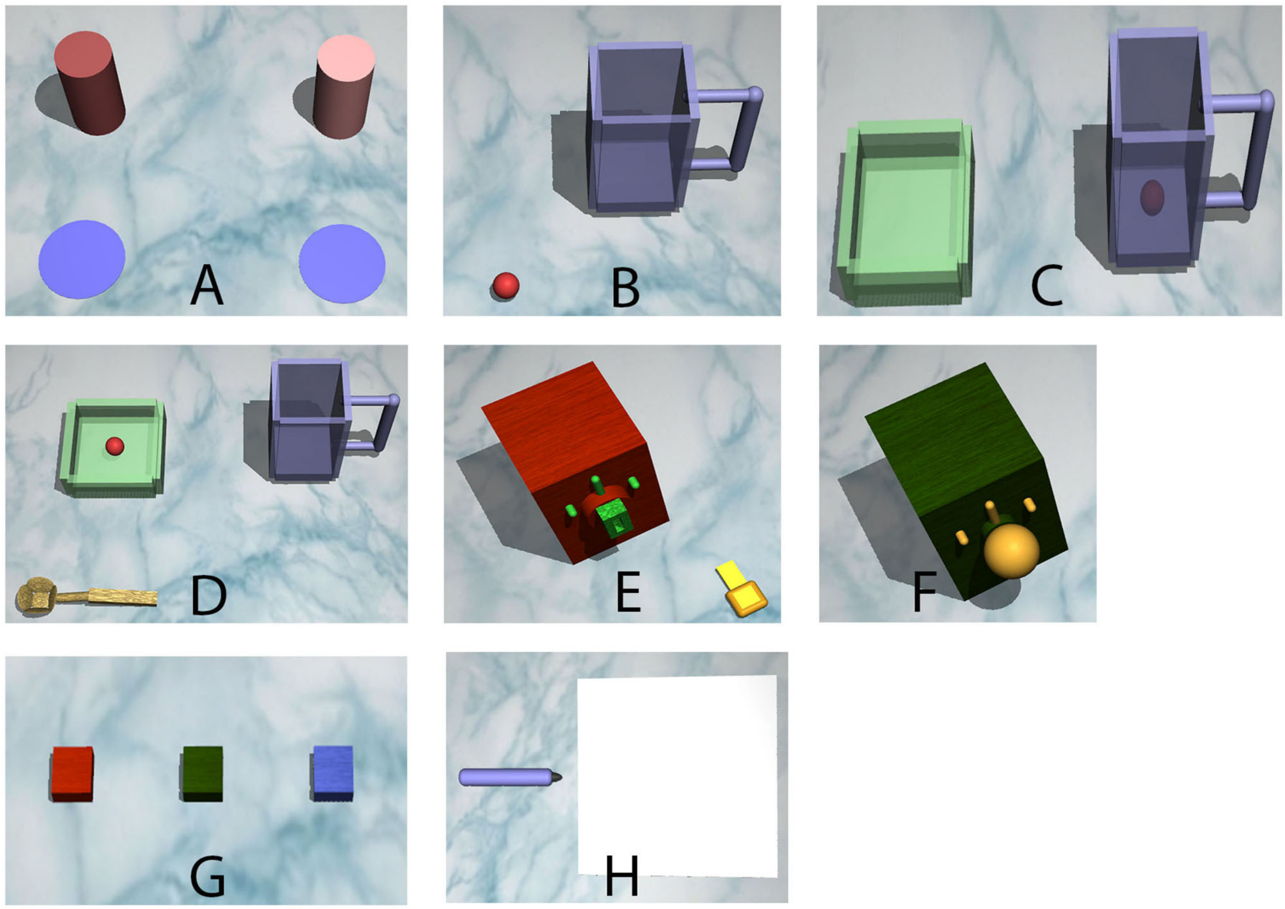

FIGURE 2 | The tasks that subjects completed. In order: **(A)** Task 1: move cans to targets, **(B)** Task 2: put ball in pitcher, **(C)** Task 3: pour ball in bowl, **(D)** Task 4: transfer ball with spoon, **(E)** Task 5: insert key and turn, **(F)** Task 6: turn knob, **(G)** Task 7: stack squares, and **(H)** Task 8: simulated writing.

TABLE 1 | Description of the tasks and task name abbreviations.

Tasks	Descriptions
1. Moving cylinders (Move Cyl.)	Pick up two cylinders and move them to targets on the table
2. Place sphere in cup (Sphere Cup)	Pick up a ball and place it in a cup on the table
3. Pour sphere in bowl (Sphere Bowl)	Pour a ball out of a cup and into a bowl
4. Spoon transfer sphere (Spoon Trans.)	Use a spoon to move a ball from a bowl to a cup on the table
5. Lock/key (Lock Key)	Pick up a key, place it into a lock, and turn the key
6. Turn doorknob (Doorknob)	Grab a door knob and turn it
7. Stack checkers (Checkers)	Stack three checkers on top of each other
8. Simulated Writing (Writing)	Pick up a pen-shaped object and pretend to write on paper

for this application. Only two subjects overlapped between the two groups due to the amount of time between completing the VR experiment and being given access to the physical prosthesis. Because participants learned techniques for completing tasks that could generalize across RW/VR environments, and we intended to measure naïve performance, our study design did not include completion of the tasks in both environments. All subjects were right-handed. No subjects reported upper limb disabilities. Subject participation was approved by the FDA IRB (RIHSC #14-086R).

Materials

Virtual Reality Equipment

The VR software used was MuJoCo HAPTIX v1.4 (Roboti, Seattle, Washington), with MATLAB (Mathworks, Natick, MA) to control task presentation. Computer and motion capture (mocap) component specifications can be found on mujoco.org/book/haptix.html. Subjects manipulated the position of the virtual hand with Motive software (OptiTrack, Corvallis, OR), mocap markers, and an OptiTrack V120: Trio camera (OptiTrack, Corvallis, OR) while using a right-handed CyberGlove III (CyberGlove Systems LLC, San Jose, CA) to control the fingers.

Real-World Equipment

The RW experiments were performed with the DEKA LUKE arm (Mobius Bionics, Manchester, NH) attached to a bypass harness. The bypass harness allowed able-bodied subjects to wear the prosthetic device. Inertial measurement units (IMUs), worn on the subject's feet, controlled the manipulation of the wrist and grasping (Resnik and Borgia, 2014; Resnik et al., 2014a,b; Resnik et al., 2018a,b; George et al., 2020). The objects used in the RW experiment were modeled after the ones manipulated in VR (**Supplementary Figure 1**).

Experimental Setup and Procedure

Virtual Reality Experiment

Mocap setup was performed before starting each experiment. Reflective markers were placed on the monitor, and subjects were assisted with donning the CyberGlove III and a mocap wrist component (**Supplementary Figure 2**). Subjects could only use their right hand to manipulate the virtual prosthesis. The height and spacing of the OptiTrack camera were adjusted to ensure that the subject could reach all of the virtual table (**Figure 3A**). A series of calibration movements was performed to align the subject's hand movements with the virtual hand on the screen. The movements required the subject to flex and extend his or her wrist and fingers maximally. Once the series of movements was completed, the subject moved his or her hand and observed how the virtual hand responded. If the subject was satisfied with the hand movement, then the experiment could begin.

The task environment was opened in MuJoCo, and operation scripts were loaded in MATLAB. MuJoCo recorded the subject's virtual performance for analysis. MATLAB scripts controlled when the tasks started, progressed the experiment through the tasks, and created a log file for analysis. Log files contained the task number and time remaining when the subject completed or moved on to the next task.

Task objects were presented to the subjects one at a time. Instructions were printed on the upper-right hand corner for 3 s and then replaced with a 60-s countdown timer signifying the start of the task. If the subject completed the task before time ran out, then he or she could click the next button to move on. Each task is completed twice in immediate succession. If the subject was unable to complete the task before time ran out, then the program automatically moved on to the next task. Analysis was performed on task completion, number of attempts to complete the task, and time to complete tasks.

Real-World Experiment

This experiment was performed following the VR experiment. Subjects tended to struggle with various aspects of completing task in VR. The VR tasks were replicated in RW based on the virtual models provided, and a physical version of the prosthetic was used for the experiments. This real-world follow-up experiment was performed to better understand which task characteristics need to be improved in the virtual design for more realistic comparison to its real-world counterparts.

Subjects were given a brief training session on how to manipulate the prosthesis before starting the experiment. Training was done to familiarize subjects with the control schema of the device and would be insufficient to affect the task success rates (Bloomer et al., 2018). The training began with device orientation, which included safety warnings, arm componentry, and arm control (**Figure 4**). The IMUs were then secured to the subject's shoes, and the prosthetist software for training amputees was displayed to the subjects to allow them to practice the manipulation motions. The left foot controlled the opening and closing of a hand grasp (plantarflexion and dorsiflexion movements, respectively) as well as grasp selection (inversion and eversion movements, respectively). The right foot controlled wrist movements: flexion and extension (plantarflexion and dorsiflexion movements, respectively), as well as pronation and supination (inversion and eversion movements, respectively). The speed of the hand and wrist movement was proportional to the steepness of the foot angle; the steeper the angle, the faster the motion. A reference sheet displaying foot controls and the different grasps was placed on the table for subjects to reference throughout training and the experiment.

Subjects were given a total of 10 min to practice the device control scheme. The first 5 min was used to practice controlling a virtual version of the device in the prosthetist software, and the next 5 min was used to practice wearing the device and performing RW object manipulation.

Training objects were removed from the table at the end of training, and the task objects were brought out. A camera captured subjects' task completion attempts for later analysis. For each task, objects were placed on the table in the locations in which they would appear in VR (**Figure 3B**). Subjects could select the grasp they wanted to use and ask any questions after hearing the explanation of the task. Grasps could be changed during the attempt to complete the task, but the task timer would not be stopped. The experimenter started the camera after confirming with the subject that they were ready to begin. Task completion, attempts, time to complete, and additional observations were recorded by the experimenter as the subject attempted to complete the task (**Supplementary Figure 3**).

The primary differences between the VR and RW setups were the control schemes used and training. This study focused on examining what characteristics can make a task difficult to complete in VR where subjects can manipulate the virtual device with their hand. This was done to show a best-case scenario control scheme. In the VR setup, subjects used a CyberGlove to control the virtual prosthetic. This allowed subjects to use their hand in a manner that replicated normal motion to complete object manipulation tasks; therefore, no training was necessary. The RW experiment used a different control scheme because the only marketed configuration of the DEKA limb uses foot control. Since the subjects were able-bodied individuals with no UL, impairment training was provided on device operation.

Virtual Reality and Real World Data Analysis

Task completion rate, number of attempts, task completion time, and movement quality were examined to evaluate task design in VR and compare against RW results. These attributes were chosen because they could provide a comparative measure of task difficulty. A task analysis was performed to decompose the tasks

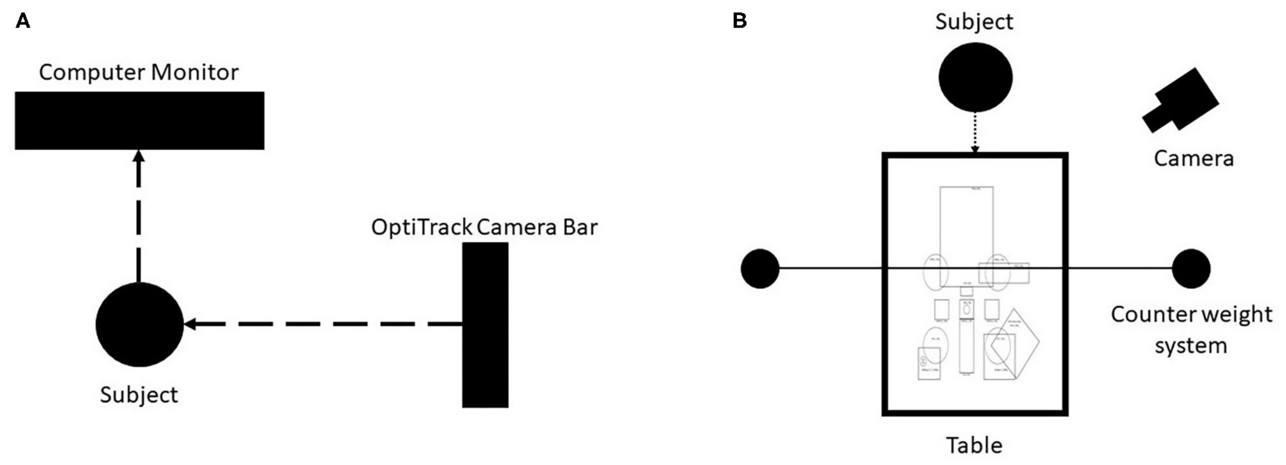

FIGURE 3 | Virtual reality (VR) and real-world (RW) experiment setups. **(A)** VR setup: Subjects were seated in front of a computer monitor, and a motion capture camera was placed to their right. The height and placement of the camera was adjusted to allow subjects to interact with the virtual table. **(B)** RW experimental setup. The subject sat in front of the table with a camera to their left to capture their performance for later review. A template was placed on the table to match where the objects would appear in the virtual environment. A counter-weight system was used to offset the torque placed on the subject's arm by the DEKA Arm bypass attachment.

into subtasks that must be completed to complete the task. Task completion is binary; if a subject partially completed a task, then it was marked as incomplete. Completion rate was calculated by summing the total number of completions and dividing it by the total number of attempts across all subjects. Subtasks were also rated on a binary scale for completion to better understand what parts of a task posed the most difficulty. This information, paired with object characteristics and interactions, provided insight into each activity and the motion requirements.

Task attempts were defined as the number of times a subject picked up or began interacting with an object and began movement toward task completion. Attempts at each of the subtasks was examined as well. Since there were numerous techniques a subject could use to complete the tasks, each subject's recording of their performance was reviewed.

Time remaining for the VR tasks was converted to completion time by subtracting the time remaining from the total time. Completion time, a continuous variable, was defined by how much time it took subjects to complete a task. Completion time for the subtasks and the tasks as a whole was compared to understand whether object characteristics and interactions affected task difficulty.

Movement quality was defined by the amount of awkwardness and compensatory movements a subject used during their attempts to complete a task (Resnik et al., 2013; van der Laan et al., 2017). Compensatory movements are atypical movements that are used to complete tasks, e.g., exaggerated trunk flexion to move an object (Resnik et al., 2013). These compensatory movements, along with adding extra steps toward subtask completion such as repeatedly putting an object back on the table to reposition it in the hand add awkwardness to how a subject moves (Levin et al., 2015). The amount of awkwardness and compensatory movements are expected to negatively impact movement quality. A scale, based on the one developed in the AM-ULA, was used to quantify movement quality for each subtask. In the AM-ULA, a five-point Likert scale is used where 0 points are given if a subject is unable to complete a task and four points are given if the subject completes the task with no awkwardness. The lowest score received for a subtask in the AM-ULA is the score given for the entire task. Reducing a task score down to one value was not performed in this experiment to provide granularity and insight into which subtasks caused the most difficulty for subjects. A modified version of this scale was used to assess the subtasks of each task. This modified scale rated movement quality on a four-point numerical scale; 1, meaning the subject moved very awkwardly with many compensatory movements, to 4, meaning excellent movement quality with no awkwardness or compensatory movement. A score of N/A was recorded if a subject did not progress to the subtask before running out of time.

To analyze the data, log files were run through a custom MATLAB script (publicly available at github.com/dbp-osel/DARPA-HAPTIX-VR-Analysis), and the VR recordings were played in an executable included with MuJoCo. The VR recordings were inspected to verify that the task was completed and to identify the number of attempts to complete a task. The task log file was exported at the end of each experiment containing the task completion time for off-line analysis. Statistical analysis was performed with a custom script written in R. A McNemar test was used compare completion rate differences. A Mann–Whitney U test was used to compare attempt rate and completion time. All statistical tests were run with $\alpha = 0.05$ and with Bonferroni correction. The tasks were compared to determine whether there was a significant difference in task difficulty based on task design. Subtasks scores and values (e.g., time in seconds) were averaged across all subjects for each

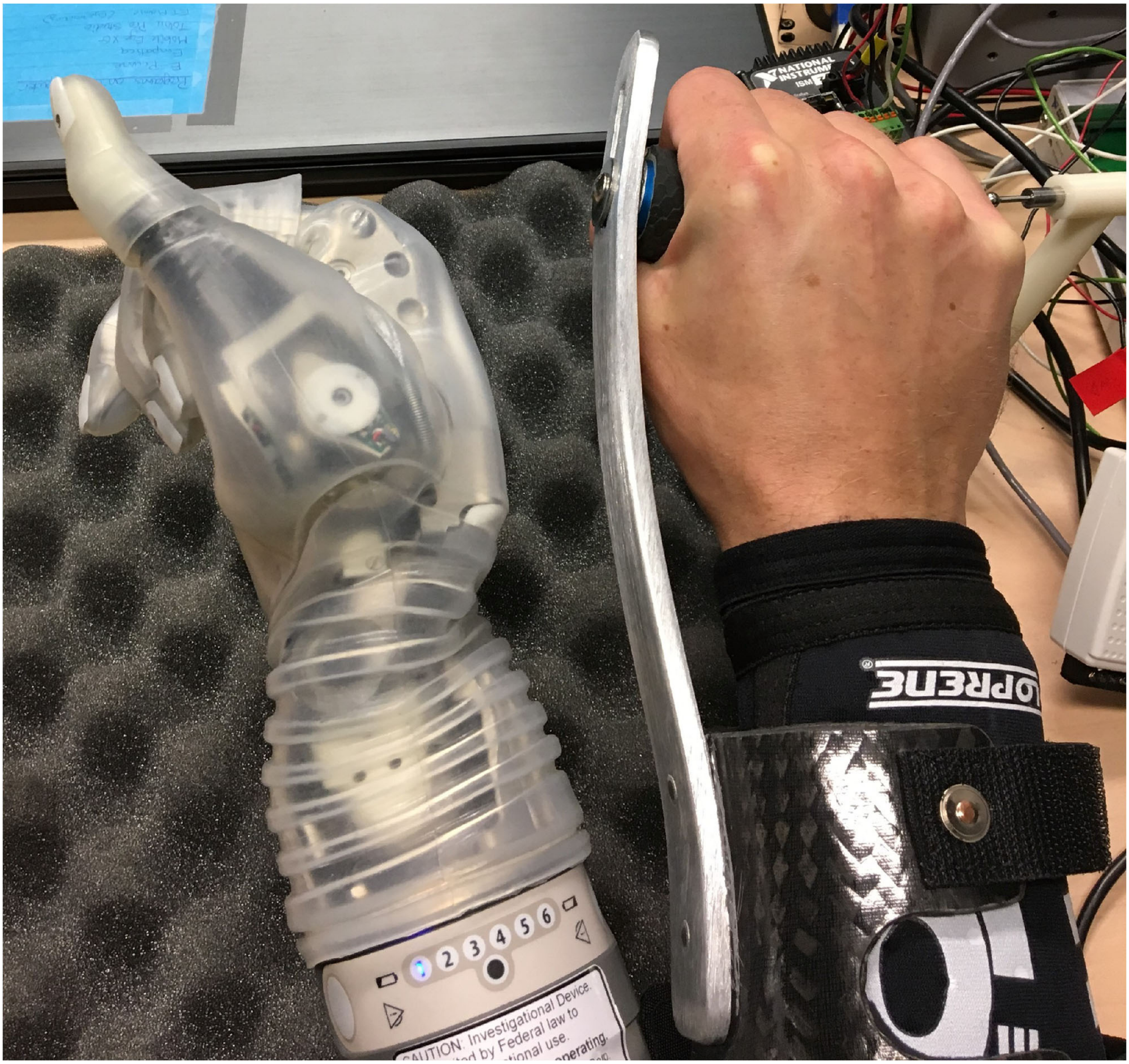

FIGURE 4 | The DEKA Arm was attached to a bypass to allow able-bodied individuals to wear the prosthesis.

of the high-level tasks. This provided a quick view of which subtasks were the most difficult for subjects to complete.

RESULTS

Virtual Reality Task Completion Rate

Tasks Sphere Cup, Spoon Tran., Lock Key, and Checkers could not be completed by the subjects ($p = 1$), as shown in **Tables 2**, **3** (statistical comparison of task completion rate in VR for all tasks; p-values produced from the McNemar test where $\alpha = 0.05$). Values with an * and highlighted in gray were found to be statistically significant. The completion rate for Move Cyl was not significantly different from the aforementioned tasks ($p = 0.0625$). Tasks Sphere Bowl, Doorknob, and Writing had the highest completion rates and were found to have a statistically significant difference ($p < 0.05$) from tasks Sphere Cup, Spoon Tran., Lock Key, and Checkers. Of the seven subtask actions (reach, grasp, pick up, place, release, move, and rotate), the reach action had the highest completion rate regardless of the high-level task (82.73%) (**Tables 4**, **5**).

Virtual Reality Task Completion Time

Since tasks Sphere Cup, Spoon Tran., Lock Key, and Checkers could not be completed by the subjects, there was no completion

TABLE 2 | Summary of analyzed task characteristics for virtual reality (VR) and real world (RW).

Tasks	VR completion rate (%)	RW completion rate (%)	VR avg. attempt rate (avg ± std)	RW avg. attempt rate (avg ± std)	VR avg. completion time (s ± std)	RW avg. completion time (s ± std)
1. Move Cyl.	11	90	3.61 ± 2.18	1.48 ± 0.88	4.8 ± 14.47	29.84 ± 16
2. Sphere Cup	0	100	1.87 ± 1.51	1.1 ± 0.37	0	11.34 ± 10.33
3. Sphere Bowl	32	98	1.37 ± 0.89	1 ± 0	8.5 ± 13.96	18.26 ± 11.69
4. Spoon Trans.	0	74	4.09 ± 1.65	1.84 ± 1.55	0	31.75 ± 14.3
5. Lock Key	0	26	5.45 ± 2.7	3.36 ± 1.87	0	43.59 ± 17.82
6. Doorknob	100	100	1.5 ± 0.7	1.32 ± 0.8	11.24 ± 4.92	13.23 ± 12.1
7. Checkers	0	100	5.86 ± 2.38	1.18 ± 0.5	0	20.06 ± 9.52
8. Writing	43	100	4.52 ± 2.35	1.32 ± 0.71	14.38 ± 19.94	20.16 ± 11.27

TABLE 3 | Statistical comparison of task completion rate in VR for all tasks.

	1. Move Cyl.	2. Sphere Cup	3. Sphere Bowl	4. Spoon Tran.	5. Lock Key	6. Doorknob	7. Checkers
2. Sphere Cup	0.625						
3. Sphere Bowl	0.0039*	0.0001*					
4. Spoon Tran.	0.625	1	0.00012*				
5. Lock Key	0.625	1	0.00012*	1			
6. Door-knob	3.6E−12*	1.1E−13*	1.86E−9*	1.1E−13*	1.1E−13*		
7. Checkers	0.625	1	0.00012*	1	1	1.1E−13*	
8. Writing	0.0001*	3.82E−6*	0.00012*	3.82E−6*	3.82E−6*	5.9E−8*	3.82E−6*

*p-values were produced from the McNemar test where α = 0.05. Values with a * and highlighted in gray were found to be statistically significant.*

TABLE 4 | Summary of analyzed subtask characteristics for VR and RW.

Subtasks	VR completion rate (%)	RW completion rate (%)	VR avg. attempt rate (avg ± std)	RW avg. attempt rate (avg ± std)	VR avg. completion time (s ± std)	RW avg. completion time (s ± std)	VR avg. motion quality score	RW avg. motion quality score
Reach	82.73	98.41	1.03 ± 0.84	1 ± 0	5.96 ± 8.55	0.98 ± 0.14	2.48 ± 0.69	3.59 ± 0.6
Grasp	31.14	98.41	4.48 ± 3.83	1.48 ± 1.24	0.99 ± 0.08	0.97 ± 0.17	1.48 ± 0.81	3.48 ± 0.7
Pick up	26.26	98.99	0.3 ± 0.55	1.31 ± 0.37	3.95 ± 8.66	0.98 ± 0.14	2.36 ± 0.89	3.39 ± 0.98
Place	5.3	99.24	1.31 ± 0.68	0.77 ± 0.49	3.25 ± 0.96	0.76 ± 0.43	1.96 ± 0.95	2.58 ± 1.62
Release	5.91	100	0.07 ± 0.25	0.99 ± 0.17	1.26 ± 0.9	0.62 ± 0.49	2.63 ± 0.95	3.56 ± 0.71
Move	27.02	99.5	1.24 ± 1.11	1.02 ± 0.29	8.3 ± 10.83	0.99 ± 0.1	2.14 ± 0.82	3.43 ± 0.8
Rotate	26.36	97.73	0.58 ± 1.13	1.13 ± 1.08	2.55 ± 5.13	0.96 ± 0.2	1.68 ± 0.74	2.59 ± 1.5

time data to compare between them resulting in no p-values to report. The remaining tasks were all found to have a statistically significant difference in completion time ($p < 0.05$) (**Table 6**). On average, subjects took the longest to complete the reach and move actions; taking 5.96 ± 8.55 s and 8.3 ± 10.83 s, respectively (**Tables 4**, **5**).

Virtual Reality Task Attempt Rate

The average number of attempts at a task can be seen in **Figure 7**. Tasks that had a higher average attempt rate were most often found to have a lower completion rate. Tasks Sphere Cup, Sphere Bowl, and Doorknob had no statistical difference in attempt rates ($p > 0.05$) due to their low attempt rate. Tasks Lock Key, Checkers, and Writing had no statistical difference due to their high attempt rates ($p > 0.05$). All remaining tasks varied in the number of attempts and were found to have a statistically significant difference in attempt rate from one another (**Table 7**). Subjects used the most attempts to complete the Grasp action with an average of 4.48 ± 3.83 attempts. The pick up, release, and rotate actions all had less than one attempt on average due to subjects not making it to these subtasks often (0.3 ± 0.55, 0.07 ± 0.25, and 0.58 ± 1.13 attempts, respectively) (**Tables 4**, **5**).

Real-World Task Completion Rate

Task completion rate varied between the two task environments (**Figure 5**). As mentioned previously, Sphere Bowl, Sphere Tran., Lock Key, and Checkers could not be completed in VR **Table 2**. The Doorknob task was the only task that could be completed 100% of the time in VR and RW. Subjects were able to complete

TABLE 5 | Average and standard deviation for VR characteristic values across subtasks and their high-level tasks.

		Move Cyl.	Sphere Cup	Sphere Bowl	Spoon Tran.	Lock Key	Doorknob	Checkers	Writing
Reach	MQ	2.2 ± 1	1.9 ± 0.92	2.3 ± 0.84	2.3 ± 0.7	2.4 ± 0.64	2.9 ± 0.49	1.4 ± 1.4	2.7 ± 0.66
	CR	0.85 ± 0.36	0.77 ± 0.42	0.91 ± 0.29	0.93 ± 0.25	0.98 ± 0.15	1 ± 0	0.5 ± 0.5	0.98 ± 0.15
	T	4.1 ± 3	6 ± 3.5	8 ± 5	12 ± 15	4.5 ± 2.2	3.5 ± 3.4	7.3 ± 16	4.2 ± 2.6
	AR	0.93 ± 0.37	0.98 ± 0.34	1.1 ± 0.51	1.7 ± 1.6	1.2 ± 0.45	1.1 ± 0.67	0.61 ± 1	1.1 ± 0.63
Grasp	MQ	1.1 ± 0.93	0.64 ± 0.49	1.8 ± 0.97	1.6 ± 0.83	1.1 ± 0.26	1.6 ± 0.74	0.62 ± 0.76	1.6 ± 0.78
	CR	0.23 ± 0.42	0 ± 0	0.68 ± 0.47	0.41 ± 0.5	0.023 ± 0.15	1 ± 0	0.034 ± 0.18	0.48 ± 0.51
	T	9.3 ± 10		4.1 ± 3.4		12 ± 3	2.7 ± 2.5	15 ± 14	25 ± 19
	AR	2.1 ± 1.9	1.7 ± 1.9	1.2 ± 1.6	5.9 ± 3.9	8.2 ± 3.7	1.2 ± 0.57	4.1 ± 4.6	6.5 ± 3.4
Pick up	MQ	0.49 ± 1		1.6 ± 1.2	1.4 ± 1.4	0.18 ± 0.69		0.17 ± 0.7	1.2 ± 1.4
	CR	0.24 ± 0.43		0.7 ± 0.46	0.55 ± 0.5	0.068 ± 0.25		0.045 ± 0.21	0.48 ± 0.51
	T	1.3 ± 2		1.8 ± 1.3	9.3 ± 13	0.86 ± 0.45		16 ± 21	1 ± 0.56
	AR	0.26 ± 0.51		0.73 ± 0.5	0.8 ± 0.9	0.068 ± 0.25		0.068 ± 0.3	0.48 ± 0.51
Place	MQ	0.4 ± 0.92						0.11 ± 0.47	
	CR	0.16 ± 0.37						0 ± 0	
	T	2.9 ± 1.8							
	AR	0.28 ± 0.61							
Release	MQ	0.43 ± 1.1						0.023 ± 0.21	
	CR	0.15 ± 0.36						0 ± 0	
	T	1.3 ± 0.9							
	AR	0.16 ± 0.37						0.011 ± 0.11	
Move	MQ	2.1 ± 1.2		1.2 ± 0.97	0.43 ± 0.81			0.12 ± 0.58	1.2 ± 1.4
	CR	0.84 ± 0.37		0.68 ± 0.47	0.18 ± 0.39			0.03 ± 0.17	0.45 ± 0.5
	T	14 ± 11		3.7 ± 1.8	13 ± 17			1.9 ± 2.9	1.4 ± 1.2
	AR	0.84 ± 0.37		0.73 ± 0.5	0.6 ± 1.5			0.045 ± 0.21	0.48 ± 0.51
Rotate	MQ			1 ± 0.96	0.15 ± 0.42		1.9 ± 0.75		
	CR			0.32 ± 0.47	0 ± 0		1 ± 0		
	T			7.9 ± 8	1 ± NA		0.66 ± 0.61		
	AR			1.1 ± 1.8	0.39 ± 1.1		1 ± 0		

Movement quality (MQ)–1–4 numerical scale, completion rate (CR)-–0–1%, time (T)—seconds, and attempts—continuous count. Black cells block cells where there were no data to analyze due to the subtask not being required to complete the high-level task or no subject data to analyze.

TABLE 6 | Statistical comparison of task completion time for all tasks in VR.

	1. Move Cyl.	2. Sphere Cup	3. Sphere Bowl	4. Spoon Tran.	5. Lock Key	6. Doorknob	7. Checkers
2. Sphere Cup	0.023*						
3. Sphere Bowl	0.039*	5.57E−5*					
4. Spoon Tran.	0.023*	N/A	5.57E−5*				
5. Lock Key	0.023*	N/A	5.57E−5*	N/A			
6. Door-knob	4.72E−11*	5.86E−18*	0.001*	5.86E−18*	5.86E−18*		
7. Checkers	0.023*	N/A	5.57E−5*	N/A	N/A	5.86E−18*	
8. Writing	0.0012*	1.29E−6*	0.200	1.29E−6*	1.29E−6*	0.11	1.29E−6*

*p-values produced from the Mann–Whitney U test with Bonferroni correction where α = 0.05. Values with an * and highlighted in gray were found to be statistically significant. Cells with N/A had no data to be compared.*

all seven subtask actions with over 95% accuracy regardless of the high-level task (**Tables 4**, **8**).

Real-World Task Completion Time

On average, subjects were able to complete the majority of the tasks faster in RW than in VR (**Figure 6**). The Doorknob task was the only task that subjects were able to complete faster in VR than in RW. If a task could not be completed, then the data were excluded from the summary statistics. Subjects were able to complete all seven subtask actions in < 1 s on average, regardless of the high-level task (**Tables 4**, **8**).

Real-World Task Attempt Rate

On average, subjects required more attempts to complete tasks in VR than in RW (**Figure 7**). The Lock Key and Checkers tasks

TABLE 7 | Statistical comparison of task attempt rate for all tasks in VR.

	1. Move Cyl.	2. Sphere Cup	3. Sphere Bowl	4. Spoon Tran.	5. Lock Key	6. Doorknob	7. Checkers
2. Sphere Cup	9.32E−5*						
3. Sphere Bowl	1.53E−8*	0.098					
4. Spoon Tran.	0.140	5.93E−9*	5.79E−13*				
5. Lock Key	0.0002*	3.93E−12*	4.27E−15*	0.002			
6. Door-knob	6.99E−8*	0.279	0.238	4.8E−13*	2.33E−15*		
7. Checkers	2.52E−5*	5.85E−12*	1.49E−14*	0.0002*	0.288	1.37E−14*	
8. Writing	0.059	1.79E−8*	5.72E−12*	0.595	0.036*	6.74E−12*	0.006*

*p-values produced from the Mann–Whitney U test with Bonferroni correction where α = 0.05. Values with an * and highlighted in gray were found to be statistically significant.*

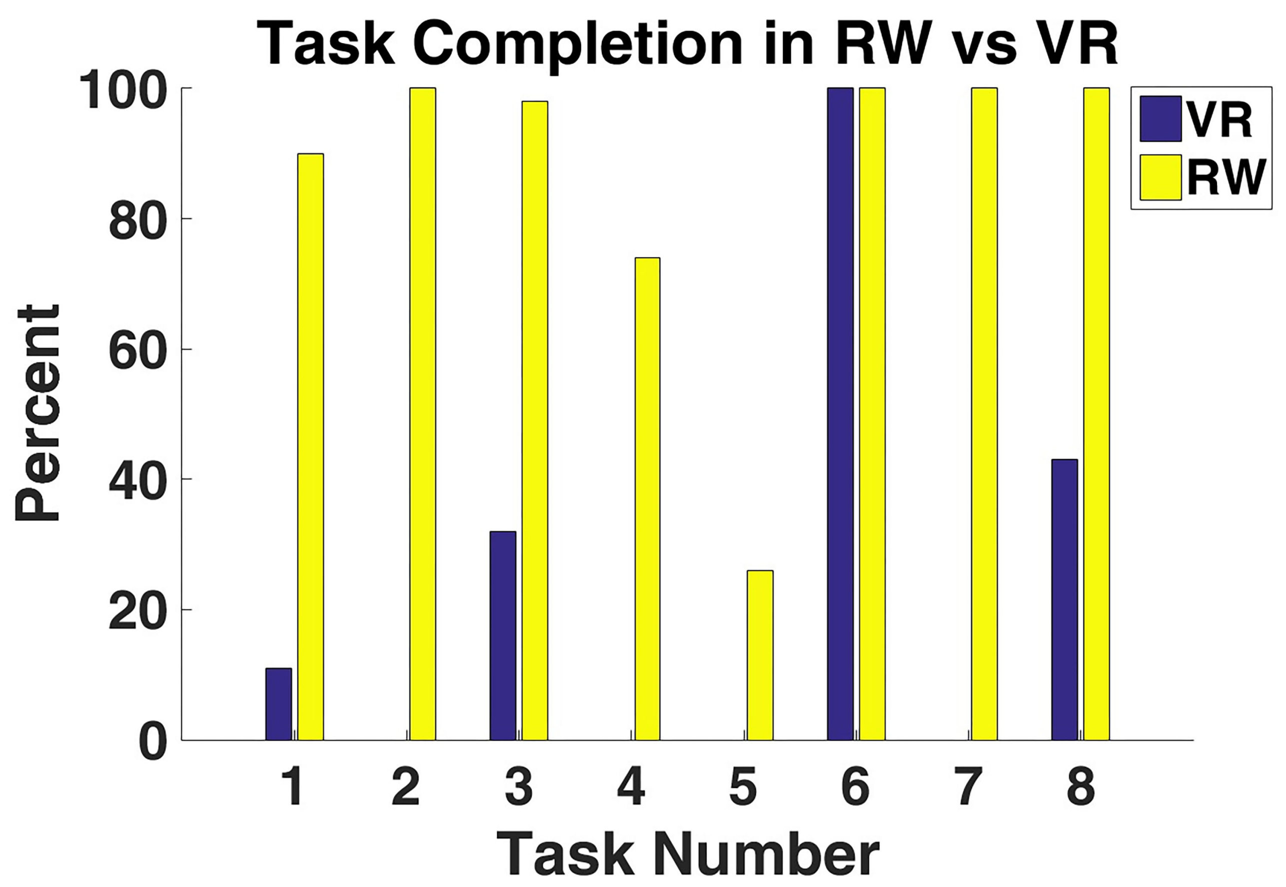

FIGURE 5 | VR and RW task completion percentage for all subjects. Subjects were only able to complete a subset of the tasks in VR, while they were able to complete all the tasks in RW.

took the most attempts to complete in VR. The Spoon Tran. and Lock Key tasks required the most attempts in RW. Most subtask actions took an average of approximately one attempt to complete (**Tables 4**, **8**).

Motion Quality and Subtask Analysis

Tables 5, **8** present the average and standard deviations for motion quality (MQ), completion rate (CR), time (T), and attempt rate (AR) for VR and RW, respectively. All subtask actions were not required across all tasks, and in some cases, subjects did not attempt to complete the subtask; these areas are marked with "NA" on the table. Across all tasks in VR, the reach action had the highest average motion quality (>2 points), denoted in green on the table. Completion rate was above 80% for subtasks with a motion quality score greater than two points in VR. Subtask actions that had a motion quality score of less than

TABLE 8 | Average and standard deviation RW characteristic values across sub-tasks and their high-level tasks.

		Move Cyl.	Sphere Cup	Sphere Bowl	Spoon Tran.	Lock Key	Doorknob	Checkers	Writing
Reach	MQ	3.7 ± 0.68	3.6 0.57	3.9 0.21	3.5 0.54	3.5 ± 0.52	3.9 ± 0.21	3.5 ± 0.46	3 ± 0.9
	CR	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0
	T	2.6 ± 2.1	2.3 ± 1.5	2.6 ± 2	2.4 ± 1.5	2.2 ± 1.6	2.2 ± 1.5	1.6 ± 1.6	2.9 ± 2.2
	AR	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0	1 ± 0
Grasp	MQ	3.6 ± 0.73	3.6 ± 0.56	3.9 ± 0.24	3.4 ± 0.59	3.1 ± 0.93	3.9 ± 0.25	3.5 ± 0.46	2.9 ± 0.97
	CR	0.99 ± 0.11	1 ± 0	1 ± 0	0.93 ± 0.25	0.6 ± 0.5	1 ± 0	1 ± 0	1 ± 0
	T	5 ± 7.9	2.6 ± 3.1	4.3 ± 2.9	7.4 ± 8.1	22 ± 15	3.9 ± 5.6	2.6 ± 3.5	8.7 ± 10
	AR	1.2 ± 0.52	1.1 ± 0.36	1 ± 0	1.8 ± 1.3	3.8 ± 2.4	1.2 ± 0.51	1.1 ± 0.33	1.4 ± 0.83
Pick up	MQ	3.6 ± 0.95	3.7 ± 0.46	3.9 ± 0.25	3.5 ± 0.56	2 ± 1.8		3.5 ± 0.46	3.2 ± 0.79
	CR	0.94 ± 0.23	1 ± 0	1 ± 0	1 ± 0	0.57 ± 0.5		0.99 ± 0.11	1 ± 0
	T	2.3 ± 5	1.4 ± 3.1	1.2 ± 1.1	5.3 ± 8.5	2.3 ± 6.6		1.4 ± 3.4	2.3 ± 5.8
	AR	1 ± 0.28	1 ± 0.21	1 ± 0	1.3 ± 0.59	0.62 ± 0.54		1.1 ± 0.28	1.1 ± 0.26
Place	MQ	3.6 ± 0.88				0 ± 0		2.5 ± 1.5	
	CR	0.95 ± 0.21				0 ± 0		0.63 ± 0.49	
	T	3.4 ± 4.8				0.7 ± 1.6		4.9 ± 7.3	
	AR	0.97 ± 0.18				0 ± 0		0.84 ± 0.55	
Release	MQ	3.6 ± 0.95	3.7 ± 0.45					3.5 ± 0.49	
	CR	0.95 ± 0.21	1 ± 0					0.95 ± 0.21	
	T	2.1 ± 2.3	2.1 ± 1.8					1 ± 1.9	
	AR	0.95 ± 0.21	1 ± 0					1 ± 0.15	
Move	MQ	3.8 ± 0.67	3.7 ± 0.44	3.8 ± 0.42	3 ± 1.2			3.5 ± 0.47	3.1 ± 0.68
	CR	1 ± 0	0.98 ± 0.15	1 ± 0	0.9 ± 0.3			1 ± 0	0.95 ± 0.22
	T	1.3 ± 0.9	1.6 ± 3.7	1.1 ± 0.53	4.3 ± 7.1			1.3 ± 2.8	5.6 ± 7
	AR	1 ± 0	1 ± 0.15	1 ± 0	1 ± 0.55			1 ± 0.21	1 ± 0.15
Rotate	MQ			2.9 ± 1.1	2.7 ± 1.3	0.92 ± 1.6	3.7 ± 0.42		
	CR			0.98 ± 0.15	0.74 ± 0.44	0.24 ± 0.43	0.88 ± 0.33		
	T			6.5 ± 4.3	9.7 ± 13	7.2 ± 11	5.5 ± 8.5		
	AR			1 ± 0.15	1.6 ± 1.5	0.29 ± 0.51	1.2 ± 0.5		

Movement quality (MQ)–1–4 numerical scale, completion rate (CR)-–0–1%, time (T)—seconds, and attempts—continuous count. Black cells block cells where there were no data to analyze due to the subtask not being required to complete the high-level task or no subject data to analyze.

two points (denoted in red on the table) had a completion rate that was $< 50\%$ on average.

In the RW environment, the only subtask action to have an average motion quality score < 1 was rotate during the Lock and Key task with an average score of 0.917 ± 1.58 (**Table 8**). Tasks with a motion quality score above tow points had an average completion rate above 50%.

DISCUSSION

Virtual Reality and Real-World Task Completion Rate

Tasks with a low completion rate were difficult due to task characteristics and potential object interactions (**Supplementary Table 2**). Subjects' task performance varied greatly between the two used environments. In VR, subjects struggled to complete Move Cyl., Sphere Bowl, and Writing tasks while being completely unable to complete Sphere Cup, Spoon Trans., Lock Key, and Checkers tasks. In the RW, subjects were able to complete all the tasks, but struggled the most with the Lock Key task. The differences in performance can be attributed to the contact modeling in VR and object occlusion. Subjects reported an experience of "inaccurate friction," which caused objects to slip out of the virtual hand more often than they would have in RW. Unrealistic physics in object interactions in VR has been shown to have a negative impact on a user's experience (Lin et al., 2016; McMahan et al., 2016; Höll et al., 2018). This lack of accurate physics causes a mismatch between the user's perception of what should happen and what they are seeing. Improvements are being made to physics calculations to more accurately calculate how an object should respond to touch (Todorov et al., 2012; Höll et al., 2018).

In VR, it was more difficult for subjects to see around their virtual hand to interact with the objects on the table. Because head tracking was not used in this experiment, the only way for them to see the task items from a different perspective was to use a mouse to turn the VR world camera, but this approach would provide a view that could be disorienting if it did not reflect the orientation of the hand. Object contact and occlusion also affected RW performance. In the Lock Key task, subjects

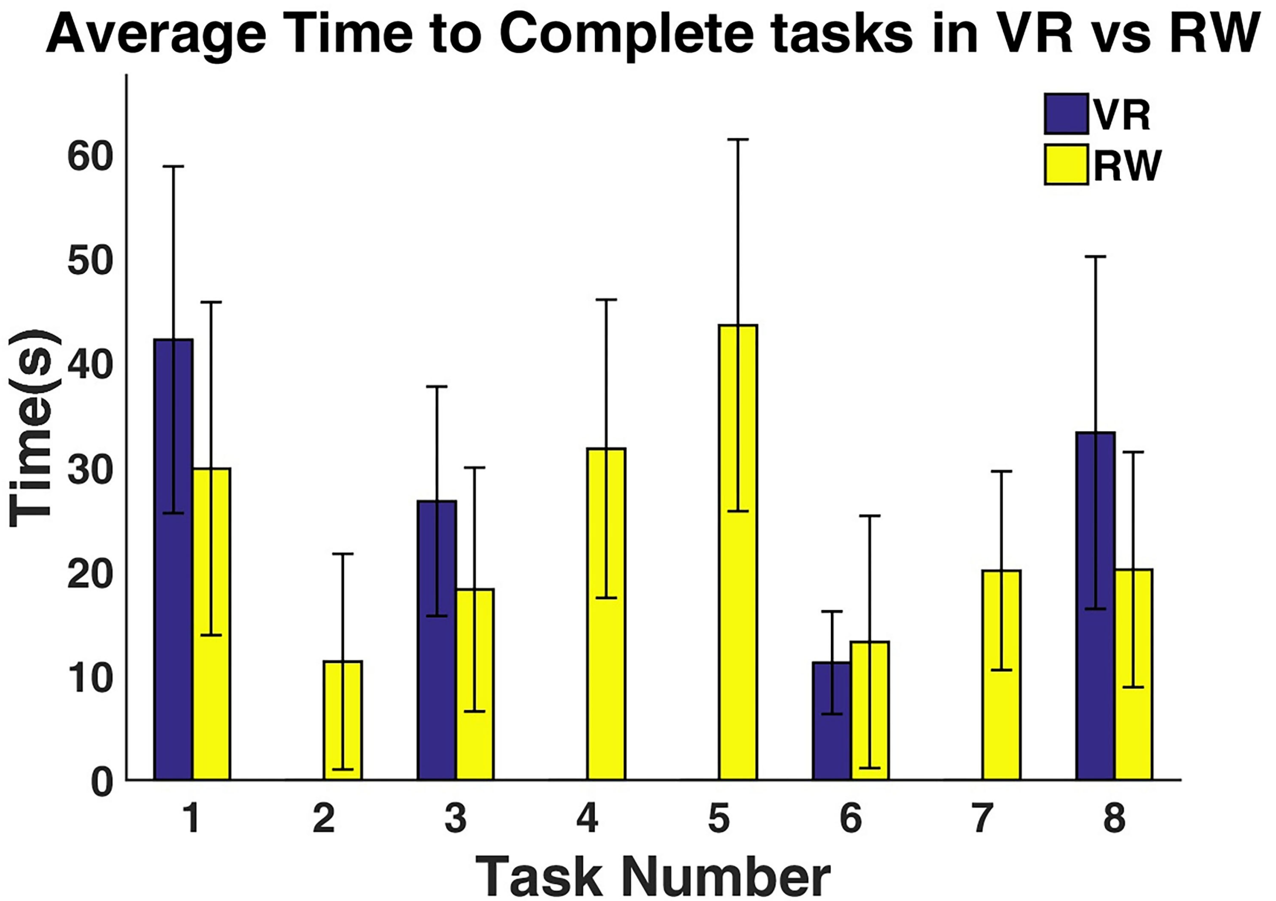

FIGURE 6 | Average time it took subjects to complete tasks in VR vs. RW. Tasks 2, 4, 5, and 7 do not have an average completion time in VR because they could not be completed. Task 6 was the only task that subjects were able to complete faster in VR than in RW. Error bars display standard deviation of the data.

tended to have difficulty picking the key up from the table and would occasionally apply too much force to the key. This would cause the key to fly off the table. The prosthetic hand would also block the subject's view of the key, thus leading the subject to lean from side to side to get a better view. There were cases where the subjects would accidently slide the key off the table when the key was occluded.

The subtask action that inhibited completion rate the most in the both environments was the grasp action (**Tables 5**, **8**). If subjects were unable to grasp an object, then they could not progress through the rest of the task. Grasp failure was caused by the object falling out of the prosthetic hand causing the subject to start over or the object falling off the table. Grasping, flexion of the fingers around an object is a necessary action to perform many ADLs (Polygerinos et al., 2015; Raj Kumar et al., 2019). Grasping requires precise manipulation of the fingers to form a grasp and apply enough force to keep an object from slipping free as well as deformation of the soft tissue in the hands around an object (Ciocarlie et al., 2005; Iturrate et al., 2018). Researchers are developing methods to allow prosthetic devices to detect object slippage as well as the design of the prosthetic itself to allow for more human-like motion or finger deformation (Odhner et al., 2013; Stachowsky et al., 2016; Wang and Ahn, 2017). The ability to grasp reliably with a prosthetic device is of high importance to amputees that use prostheses, and the lack of this ability can result in amputees choosing not to use a prosthetic device (Biddiss et al., 2007; Cordella et al., 2016).

Virtual Reality and Real-World Task Completion Time

Subjects on average were able to complete the tasks faster in RW than in VR. Object contact and occlusion affected these results as well. With each failure to maintain object contact in the RW and VR environments, subjects were required to restart the object manipulation attempt. When objects were occluded while attempting object interactions, it would take time to realize missed object pickups, or time was spent to manipulate objects into high-visibility locations to ease interactions. The door knob task was the only task subjects completed faster in VR than in RW because it was easier to turn the virtual

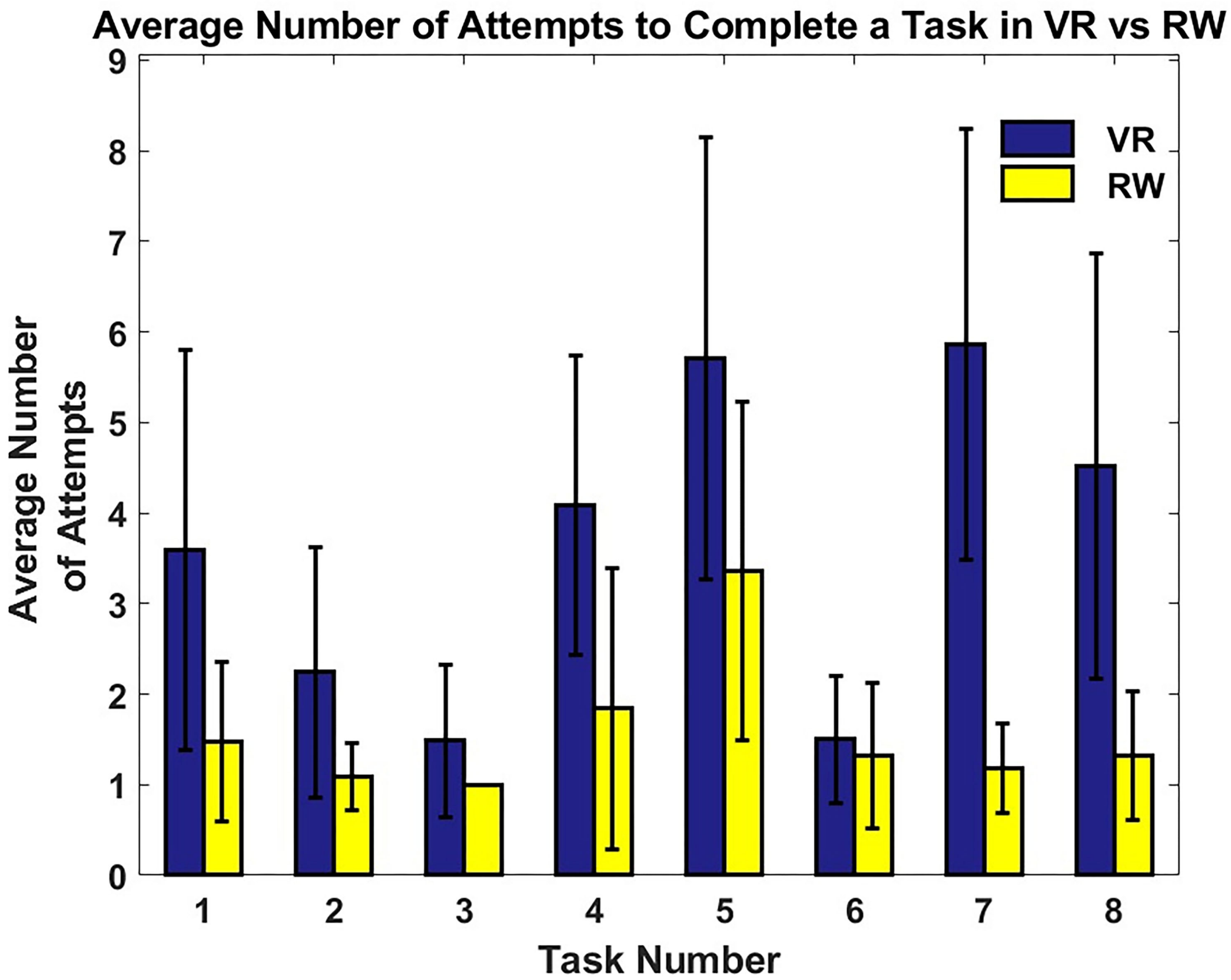

FIGURE 7 | Average number of attempts subjects made while trying to complete a task in VR vs. RW. All tasks required fewer attempts in RW than in VR. The characteristics of the items in the tasks (e.g., small size) had a more marked effect on number of attempts in VR than in RW. Error bars display standard deviation of the data.

door knob. The resistance to turn the door knob was very low; thus, minimal contact was needed. The control scheme for the RW prosthesis could have slowed down the completion time for this task as well. The rotation speed of the RW prosthesis wrist was proportional to the tilt angle of the subject's foot. For example, the Doorknob task could be completed faster if the subject used a steeper inversion angle to make the wrist rotate faster.

Virtual Reality and Real-World Task Attempt Rate

Attempt rate and completion rate were negatively correlated for most of the tasks. Tasks Lock Key and Stacking Checkers had the highest attempt rates out of all the tasks and the lowest completion rates due to small object manipulation and occlusion. This is also reflected in the increased number of attempts at the grasp subtask action in these tasks (**Tables 5**, **8**). In comparison, Tasks Sphere Bowl and Doorknob had the lowest attempt rates and high completion rates due to the manipulation of large objects or objects locked onto the table. However, Tasks Sphere Cup and Writing did not show the same negative relationship. Task Sphere Cup had a low attempt rate due to its early exclusion action that also contributed to the low completion rate. Task Writing had a high attempt rate due to the round pen being flush with the table causing it to roll away from the subjects as they attempted to pick it up. However, the subjects were able to prevent the pen from rolling off the table, allowing them to complete the task.

Repeated, ineffective attempts at completing a task can negatively impact a person's willingness to use a prosthetic device. Gamification of prosthesis training is intended to make prosthesis training more enjoyable and provide a steady stream of feedback (Tabor et al., 2017; Radhakrishnan et al., 2019), though these training games need to be designed appropriately to avoid unnecessary frustration. Training and device use frustration has been shown to cause people to stop using their device (Dosen et al., 2015).

Effect of Motion Quality on Completion Rate

Motion quality scores were positively correlated with task completion rate in both environments. Object view obstruction contributed to the decrease in motion quality scores. Subjects would flex and abduct their shoulders or perform lateral bending of their torso in an effort to view around the prosthetic device they were using. Subjects were also more likely to use compensatory movements when they knew they were running out of time to complete the task. Between the two environments, VR had lower motion quality scores, which is due to the slow movement of subjects while attempting to complete these tasks and the rushed reactions to objects moving away from them. Compensatory movements are known to put extra strain on the musculoskeletal system (Carey et al., 2009; Hussaini et al., 2017; Reilly and Kontson, 2020; Valevicius et al., 2020). This strain can eventually lead to injuries that could cause an individual to stop using their prosthesis. It is important for prosthetists to identify compensatory movements and help train amputees to avoid habitually relying on these types of motions.

Study Limitations

The lack of RW-like friction, object occlusion, and prosthesis control issues all negatively affected the results. These factors made it difficult for subjects to complete tasks, increased the amount of time needed to complete a task, and required subjects to make multiple attempts to complete the task. While task completion strategies positively impacted the results, the tactics that could be applied in one environment were not always compatible with the other environment. In RW, subjects would slide objects to the edge of the table to give themselves access to another side of the object to interact with or to make it easier to get their prosthesis under the object. This tactic could not be applied in VR due to the placement of motion capture cameras and the inability of the hand to go beneath the plane of the table top. Future VR environments should allow subjects to practice all possible RW object manipulation tactics and control in restricting possible tactics to prosthetists for training purposes. Future work will need to explore the use of within-subject design to study the translatability of findings between the two environments.

Another limitation is the difference in training between the two environments. Subjects in the VR experiment were not given training or time to practice picking up objects. The use of the CyberGlove allowed subjects to use their hand to manipulate the virtual prosthetic, therefore reducing, the need to train on device control, but subjects did not know how the virtual prosthesis and objects would interact. Practicing object manipulation on non-task-related items may have improved performance outcomes in VR. While subjects in the RW experiment were given training, it was not significant enough to impact performance. In a study by Bloomer et al., they showed that it would take several days of training to improve performance with a bypass prosthetic (Bloomer et al., 2018). The training given to subjects in this experiment was meant to provide them with baseline knowledge on how to use the device. Future work should provide light training for subjects in VR and RW to ensure that subjects have comparable baseline knowledge.

CONCLUSIONS

The results showed that performance between the two used environments can vary greatly depending on task design in VR and the used environment in RW. VR could be used to help device users practice multiple methods to complete a task to later inform strategy testing in RW.

Given the results of this study, virtual task designers should avoid placing objects flush with a table and requiring subjects to manipulate very small objects, and ensure that contact modeling is sufficient for object interactions to feel "natural." Objects that are flush with the table and small can be easily occluded. Task objects would be less likely to fall out of the virtual hand with improved contact modeling when subjects are attempting different grasps. These factors make it difficult to manipulate objects in VR, causing inaccurately poor results that limit the translatability of the training and progress tracking. The results of the move cyl., sphere bowl, doorknob, and writing tasks were most similar between the VR and RW environments, suggesting that these tasks may be the most useful for VR training and assessment.

Prosthetists using VR to assist with training should use VR environments in intervals and assess frustration with the training. Performing VR training in intervals would provide time for both the prosthetist and amputee to assess how this style of training is working. Reducing the amount of frustration will improve training and help reduce the chance of the amputee forgoing his/her prosthetic.

Additional research is needed using the same prosthesis control schemes between the two environments. Two different control schemes were used in this study, one natural control ("best-case") scenario and one with the actual prosthetic device control scheme. Even with the best-case scenario control scheme, subjects were unable to complete half of the tasks due to the aforementioned issues. A comparison of performance in VR and RW with the same control scheme would provide more insight into what types of tasks prosthetists could have amputees practice virtually. The ability to virtually practice could help amputees feel comfortable with their devices' control mechanisms and open the door for completely virtual training sessions.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Food and Drug Administration IRB. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

HB and JJ conceptualized the study, methodology, and developed the methodology. JJ, MV-C, and HB validated the study, wrote, and reviewed, and edited the article. JJ made the formal analysis, conducted the investigation and data curation, prepared and wrote the original draft, and conducted the visualization. HB provided the resources and acquired the funding. MV-C and HB supervised the study and handled the project administration. 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/frvir.2021.599274/full#supplementary-material

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BRIEF RESEARCH REPORT
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Feasibility of Using Commercially Available Accelerometers to Monitor Upper Extremity Home Practice With Persons Post-stroke: A Secondary Data Analysis

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Background: Adherence to home practice rehabilitation programs is important for efficacy; however, adherence is challenging for many individuals post-stroke. Accelerometers have emerged as a potential means to support home practice. This secondary data analysis explored the use of a commercially available accelerometer with custom software to collect and analyze data to corroborate self-reported practice collected during a home program.

Methods: The initial study was a single subject design trial that investigated the effect of preferred music listening on adherence to an upper extremity home practice program (Trial Number NCT02906956. ClinicalTrials.gov). The participants ($n = 7$) were post-stroke adults with aphasia and hemiparesis of the upper extremity. Participants completed home program exercises while wearing accelerometers and recorded practice times in a logbook. Data were collected, cleaned, processed, and analyzed to facilitate descriptive comparisons and clinical interpretations of accelerometer output data.

Results: Across all participants, an average of 47% of data were captured and usable for analysis. Five out of seven participants self-reported longer practice times compared to accelerometer duration output by a mean of 66.5 s. Individual exercise set mean total angular velocity and standard deviation of acceleration demonstrated potential for use across time to monitor change.

Conclusions: One challenge of integrating accelerometers into clinical practice is the amount of data loss and the steps for data processing. The comparisons of available accelerometer data to the self-reported logs, however, were generally representative. Future investigations should explore ways to increase data capture and accessibility of the data for feedback to the client and practitioner.

Keywords: accelerometers, rehabilatation, stroke, upper extremity, home exercise, hemiparesis

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INTRODUCTION

Hemiparesis is the most common post-stroke neurological impairment and affects participation in activities of daily living (ADLs) and meaningful occupations (Reiterer et al., 2008). Therefore, rehabilitation of the hemiparetic upper extremity is a key factor in promoting independence post-stroke. One effective rehabilitation approach to increase motor function and prevent learned non-use involves rebuilding neural connections through task repetitive practice (Lang and Birkenmeier, 2014). While this approach shows promise, clinicians have limited time to provide direct services to clients. This barrier often leads to the use of home programs to extend treatment through unsupervised practice.

One challenge clinicians face when monitoring home programs is the limited ability to track adherence to programs. There are two approaches commonly reported in the literature to measure adherence to home programs: self-report *via* journal/diary/logbook or use of a technological method to track activity (Frost et al., 2017; Donoso Brown et al., 2020a). The ability to monitor adherence using technology would allow for provision of timely feedback as well as reminders to engage in exercises. Examples of technology include pedometers, virtual reality gloves, computer games, and accelerometers (Standen et al., 2015; Donoso Brown et al., 2020a).

Wrist-worn accelerometers may be particularly useful for tracking adherence to upper extremity home programs because they are non-invasive, portable, and light weight. In addition, tri-axial accelerometers are able to measure acceleration in three perpendicular planes (X, Y, Z). The portable and non-invasive nature of these devices promotes the ability to wear them in a real-world environment (Uswatte et al., 2006; Noorkõiv et al., 2014; Bailey et al., 2015; Urbin et al., 2015). Another appealing aspect of this device is that there are accelerometers incorporated into commercially available activity monitors (i.e., smartwatches), which could increase accessibility.

Research grade accelerometers, specifically, have been found to be valid and reliable tools for measuring upper extremity activity among adults with and without stroke (Bailey et al., 2015; Urbin et al., 2015). In previous research with persons post-stroke, Noorkõiv and colleagues used accelerometry to identify active and inactive periods of hemiparetic upper extremity movement (Noorkõiv et al., 2014). Additionally, Lee et al. (2018) found that accelerometers can differentiate between goal-directed and non-goal directed movements with 87% accuracy. Accelerometers can also compare right and left upper extremity movement, thus allowing clinicians to monitor learned non-use, which cannot be otherwise measured using standardized stroke assessments (Reiterer et al., 2008; Bailey et al., 2015). Finally, accelerometer data has been found to correlate with standardized measures of upper extremity function, which provides some evidence of the potential for this device to monitor progression in the real-world environment across the period of time when they are being worn (Uswatte et al., 2006; Reiterer et al., 2008). Despite the benefits of using accelerometers to monitor post-stroke upper extremity rehabilitation, there remain challenges regarding data capture and management. For example, Uswatte et al. (2006) completed a study in which participants wore accelerometers for two 3-day periods; however, researchers lost 23% of accelerometer data due to errors with downloading and storing data, participant error when wearing the devices, and technological failure. Additionally, data output from accelerometers can be difficult to process and interpret intuitively (Urbin et al., 2015).

In addition to these challenges, most investigations in individuals post-stroke have explored the use of research grade accelerometers rather than commercially available devices (Noorkõiv et al., 2014). One benefit of commercially available accelerometers is the variety of wristband designs which could increase independence in doffing and donning the device when in use (Lee et al., 2018). Additional benefits found in an investigation of the Fitbit® (Rowe and Neville, 2019) include accessibility, affordability, and provision of immediate feedback. Rowe and Neville (2019) compared the Fitbit®, to the gold standard accelerometer, ActiGraph® in healthy adults. The results found that while less sensitive to the capture of upper extremity movement measured *via* step count, the data from both devices was strongly correlated (i.e., $r > 0.8$). Similarly, the commercially available Microsoft Band™ has been found to consistently track duration, angular velocity, and acceleration as well as produce anticipated data outcomes when worn by healthy adults during task-repetitive exercises (Gough et al., 2019). While these studies outline some benefits of using commercially available accelerometers and indicate preliminary psychometric information, there is limited research available regarding the use of these devices for monitoring home exercise programs for persons post-stroke. Therefore, the objective of this secondary data analysis was to understand elements of practicality related to use of a commercially available accelerometer with custom software programs to corroborate self-reported data and provide information on characteristics of practice when completing an upper extremity home program. We sought to answer three research questions:

(1) What percentage of self-reported practice sessions were recorded by accelerometers during the home exercise program?
(2) How does self-reported practice duration of a home program compare to the recorded duration captured *via* accelerometry?
(3) What can accelerometer outputs, such as angular velocity and acceleration, tell us about speed or movement quality during practice over time?

Five variables related to accelerometer data were explored during data analysis, including (1) data capture (%); (2) duration (s); (3) percent active time (%); (4) angular velocity (degrees/s); and (5) standard deviation of acceleration (m/s^2) in the X, Y, and Z planes.

METHODS

Initial Study Background

These data were collected during a single subject design intervention study (ABAB) to evaluate the impact of preferred music listening during home program practice on adherence

(Donoso Brown et al., 2020b). Seven stroke survivors in the chronic phase of recovery participated in the original study. Participants ranged from 45 to 83 years in age (Mean = 63.43; SD = 16.7) and experienced right upper extremity hemiparesis and mild to moderate aphasia (Donoso Brown et al., 2020b). See **Supplementary Table 1** for details of participant demographics. Results from the original study indicate that four participants met or exceeded the target of 10 practice sessions per week (Donoso Brown et al., 2020b). The remaining participants fell below 10 practice sessions per week for at least 1 week during the study period and no consistent effect of preferred music listening was found. Additionally, participants reported their experiences with the bands as motivating although some reported needing assistance to put them on prior to practicing (Wallace et al., 2018).

Secondary Analysis

The secondary data analysis presented is a descriptive quantitative analysis of the metrics obtained from the accelerometer worn on the paretic limb during home practice. When applicable, metrics such as number of exercises and duration, were compared to data collected *via* self-report by the participants in their logbooks.

Data Collection

During data collection, participants wore one commercially available activity monitor (Microsoft Band™) on each wrist while completing several, task repetitive exercises, with rest breaks between sets, in their home environment. The exercises varied for each participant, as the initial study assessed adherence to home exercise programs. Exercises were selected based on activities that were meaningful and motivating to each participant as well as their upper extremity level of impairment. See **Supplementary Table 1** for each participant's exercises. Practice sessions consisted of two to three different exercises. Participants were typically instructed to practice each exercise in three sets of 20 repetitions. During breaks between each individual exercise set, participants were asked to rest their hands to aid in data processing. Participants were asked to complete two practice sessions per day, 5 days a week, for 4 weeks. In the logbooks, participants recorded the start time and stop time for each exercise, number of individual exercise sets for each exercise, and number of repetitions completed within each individual exercise set.

The Microsoft Band™ was connected to a mobile phone, which was not connected to a cellular or wireless network. The phone contained an application developed by Venetasoft, Children's National Hospital, and the University of Pittsburgh, which was provided to the authors by request, to extract raw data from the Microsoft Band™'s triaxial accelerometer and gyroscope. The frequency of data collection was set at 62 hertz. The band and phone were connected by Bluetooth. The application was left running continuously during the study period to eliminate the need for participants to start and stop data collection on the devices. Participants needed to put the Microsoft Bands™ on their wrists and then record the start time prior to beginning their practice session. Participants were taught to check the phone for a green light, indicating that the application was collecting data. Additionally, participants were instructed to contact the research team if technical difficulties arose. Data were manually downloaded from the phones once per week during the study. Only data from the paretic (right) limb was analyzed.

Data Processing and Cleaning

Data captured by the accelerometer included angular velocity (degrees/s) and acceleration (m/s^2) in each of the X, Y, and Z spatial planes. These data were downloaded from the phones as .log files. Due to the size of the files, they were exported into SPSS® (IMB, Version 26) and data from each exercise were extracted based on participant-reported start and stop times in their logbooks. The data were not filtered; therefore, we used all data points collected during each exercise in our analyses. We used all data collected to ensure the variability of the metrics being studied was well-captured. Accelerometer data corresponding to each exercise were then saved as .csv files. The exercise files were then imported into Matlab® (Mathworks, Version 2020) and run one at a time through a custom program, which included a graphical interface to guide the user in each step of data importation and analysis.

The Matlab® program read the data from each .csv file and parsed it into six vectors. Three vectors contained the absolute value of angular velocity (degrees/s) in each of the X, Y, and Z planes, respectively. The other three vectors contained the absolute value of acceleration (m/s^2) in each of the X, Y, and Z planes, respectively. The absolute value was used because we were interested in the magnitude of these values and not the direction. From these six vectors, the program generated six graphs displaying angular velocity and acceleration in each of the X, Y, and Z planes over the entire length of time represented by the data set. When possible, visual inspection of the graphs was used to note patterns representative of repetitive exercise and rest periods. We also used visual inspection to identify precise start and stop times (i.e., line numbers in Matlab®) for individual exercise sets as well as total exercise. Graphs were considered readable if each individual exercise set was preceded and followed by a rest period during which the velocity values were approximately zero. As needed, multiple graphs (e.g., angular velocity X and angular velocity Y) were referenced to identify the rest periods. The start and stop times were identified as Matlab® line numbers corresponding to the times at which the participant transitioned from a rest period (zero velocity) to an individual exercise set (non-zero velocity), and vice versa. See **Figure 1** for example of resulting start and stop times from visual inspection using Matlab® output. Start and stop times had to be identifiable across all sets in the exercise in order for the data to be considered usable for individual set analysis. There were some exercises for which we were unable to visually identify distinct start and stop points, as there was no discernable pattern of activity when the data was graphed. As a result, these data were not used during analysis.

To analyze individual sets within an exercise, the start and stop times of each individual exercise set found by visual inspection were entered into the Matlab® program. The line numbers

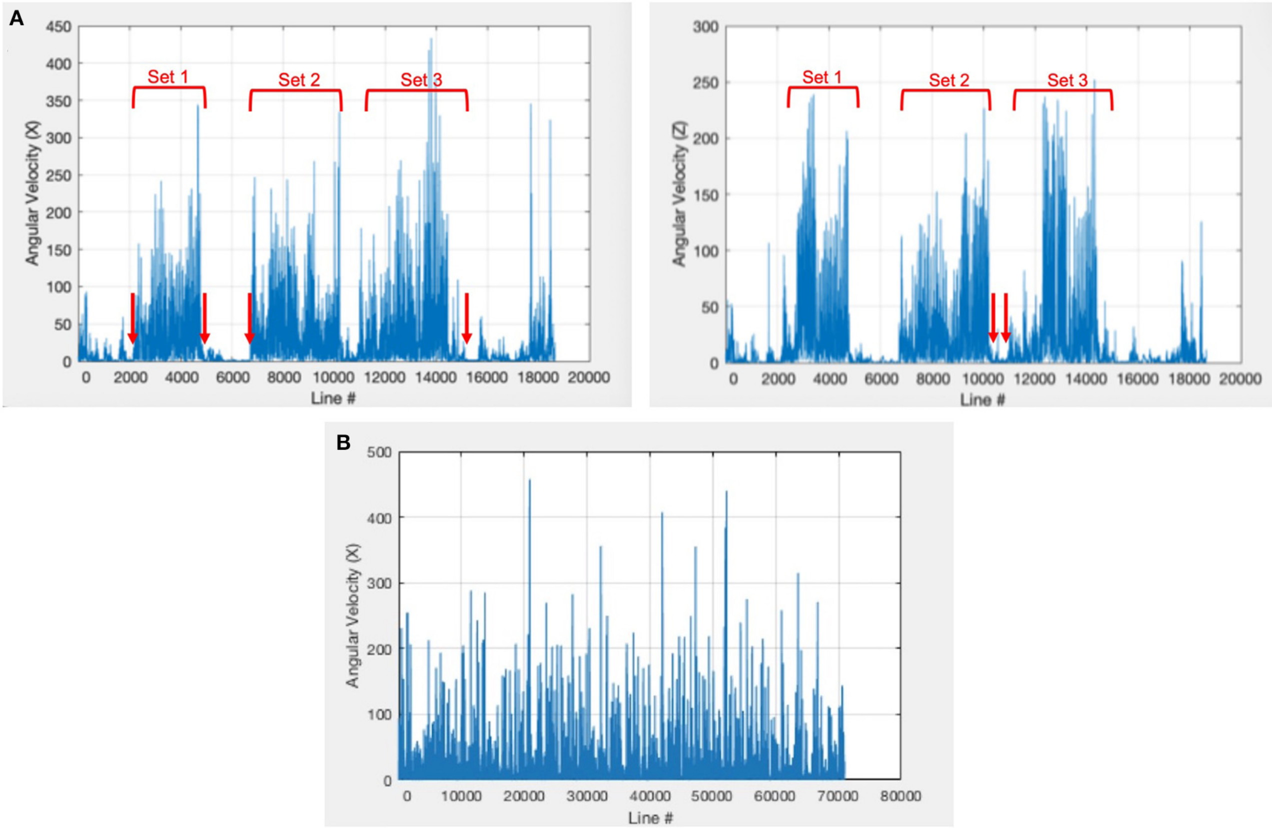

FIGURE 1 | Example Matlab® output for determination of start and stop points. Participant 3 completed three individual exercise sets during the exercise seen in graph **(A)**. We were able to visually identify start and stop points for each set. Set 1 started at line 2170 and stopped at line 4809, set 2 started at 6778 and stopped at 10320, and set 3 started at 10960 and stopped at 15200. Participant 6 reported having completed three individual exercise sets during the exercise seen in graph **(B)**; however, we were unable to visually identify three individual exercise sets when graphing the data in the custom Matlab® program: (4597, 70940).

for the start and stop times were recorded in order to allow for consistency when re-running the data for the exercise. The program then analyzed data obtained between the start and stop of each set in an exercise (i.e., beginning of first set to end of first set, beginning of second set to end of second set). These data did not include the rest periods that participants were instructed to take between individual exercise sets. The files were run through the program a second time to analyze the data for the total exercise (i.e., beginning of first set of an exercise to end of the last set of exercise). This total exercise data included rest breaks. By considering both sets of data, we were able to determine if the variables collected operated as expected in relation to the inclusion and exclusion of rest breaks.

The Matlab® program was designed to output the following variables. Duration (s) was determined by first calculating the difference in the line numbers representing the stop and start times and then converting this quantity to seconds. Duration provided a measure of practice time. The average, standard deviation, max, and min of angular velocity (degrees/s) and acceleration (m/s^2) between select start and stop times were also outputted. Angular velocity and acceleration provided measures of magnitude and variability in practice speed and were calculated for each of the X, Y, and Z directions as well as their sum (i.e., total). To answer the specific research questions outlined for this secondary analysis, the following variables were used: duration, average total angular velocity $(V_X+V_Y+V_Z)$, and standard deviation of acceleration. The standard deviation of acceleration was chosen as a primary focus because variability in acceleration has been shown to positively correlate with functional performance of the affected upper extremity post-stroke (Urbin et al., 2015).

Data Analysis

All data outputted by Matlab® were organized and further analyzed in Excel©. The sum of the durations, as well as the angular velocity and acceleration outputs from the individual exercise sets were compared to those corresponding to the total exercise. Additionally, the percentages of data capture and active time were calculated for each participant and averaged across all assigned exercises. Four analyses were completed to answer the research questions: (1) amount of exercises with usable data captured by the accelerometer vs. number of self-reported exercises; (2) self-reported exercise duration vs. accelerometer recorded duration; (3) total average angular velocity across an entire exercise vs. total average angular velocity during individual exercise sets; and (4) trends observed in total average angular velocity and the standard deviation of acceleration over time.

Data Capture

To answer the first research question, the percentage of data capture was calculated by dividing the number of exercises captured *via* the accelerometers by the number of exercises reported by participants. For each participant, the percentage of data capture was calculated for each exercise on a weekly basis and then averaged over all weeks and exercises in the study period. We then calculated the average percentage of data capture across all participants to provide a single measure of data capture for the study. A similar method was used to calculate the percentage of exercises that were unreadable or lost due to technological failure for each participant.

Duration

The accelerometer output yielded two variables related to duration: (1) individual exercise set duration; and (2) total exercise duration, which included the time spent resting between sets. For each participant, the self-reported duration, accelerometer-recorded sum of individual exercise set duration, and accelerometer-recorded exercise duration were averaged for each participant and then across all participants in the study. Descriptive comparisons were made between (1) self-reported and accelerometer-recorded exercise durations; and (2) total exercise duration and the sum of individual exercise set durations. Additionally, the percent of active practice time during each exercise was calculated using accelerometer output by dividing the average of the sum of individual exercise set durations by average total exercise duration.

Angular Velocity

The total average angular velocity from each exercise was descriptively compared with the total average angular velocity obtained over individual exercise sets to determine the impact of rest breaks on these outputs. It was anticipated that total average angular velocity as a measure of speed would be greater in the individual exercise sets, as these data did not include rest breaks. Additionally, for participants with >50% data captured ($n = 3$), the individual exercise set average for total average angular velocity in each assigned exercise was graphed as a function of time and a line of best fit was found to determine the trend in total average angular velocity over the study period. To determine if trends observed over the study period were statistically significant, an unpaired t-test ($\alpha = 0.01$) compared the first nine individual exercise sets' average total angular velocity to the last nine individual exercise sets' average total angular velocity.

Acceleration

For participants with >50% of data captured ($n = 3$), the standard deviation of acceleration in the X, Y, and Z planes was obtained for individual exercise sets and total exercise. The individual set values were then averaged within each exercise. These values were then graphed for each assigned exercise as a function of time and a line of best fit was found to determine the trend in individual exercise set average standard deviation of acceleration over the study period. In order to determine if trends observed over the study period were statistically significant, an unpaired t-test ($\alpha = 0.01$) compared the first nine individual exercise sets' average standard deviation of acceleration to the last nine individual exercise sets' average standard deviation of acceleration.

See **Supplementary Table 2** for a list of all variables and their calculation for these analyses.

RESULTS

Data Capture

Across all participants, an average of 47.27% (range 17.33–70.41%) of all self-reported exercises were captured by the accelerometers and produced corresponding usable data in Matlab®. For three out of seven participants, data were captured for >50% of all self-reported exercises (P2, P3, P6). Technological failure accounted for an average of 30.5% (range 8.3–54.8%) of the remaining self-reported exercises. Five out of seven participants lost an entire week of accelerometer data due to technological failure. An average of 19.9% (range 2.3–50.69%) of the captured data illustrated no discernable pattern of activity. See **Table 1** for details on participant data capture percentages.

Duration

Self-reported total exercise duration was longer than accelerometer-recorded total exercise duration for five out of the seven participants. These five participants reported practicing for an average of 66.5 s longer (range 5.58–182.29) than accelerometer-recorded total exercise duration. Additionally, total exercise duration was on average 85.93 s longer (range 17.33–220.59) than the sum of the individual exercise set durations. Furthermore, during exercise, six out of the seven participants were active for 75% or more of the time. The average active time percentage across the seven participants was 85.22%, ranging from 63.99 to 95.5% active time. See **Table 2** for average self-reported and accelerometer-recorded duration values for each participant, as well as active time percentages and **Supplementary Figure 1** for graphs of the difference between self-reported and accelerometer-recorded durations for each participant's assigned exercise.

Angular Velocity

Across all participants a mean difference in average total angular velocity of 15.02 degrees/s (range 0.39–51.83) was found between the individual exercise sets and total exercises (includes rest breaks). See **Table 3** for the total average angular velocity comparisons across all participants. When total average angular velocity measures were graphed over time, eight out of the nine slopes were positive with a range of 0.029–3.99. All three participants demonstrated a statistically significant increase in individual set total angular velocity in at least one activity over the study period ($p < 0.01$). P3 had the two largest positive slopes of 2.48 and 3.99. See **Supplementary Figure 2** for graphs of these data with corresponding statistical analyses.

TABLE 1 | Categorization of data capture and comparison to self-reported practice.

	Self-reported exercises (Total number)	Exercises with usable data (Percent)	Exercises with no discernable pattern of activity (Percent)	Exercises with technological failure (Percent)
P1	147	48.64	22.65	28.7
P2	117	70.41	19.87	9.7
P3	175	59.4	7.2	34.1
P4	72	41	50.69	8.3
P5	129	34.6	2.3	54.6
P6	149	59.5	17.54	22.9
P7	110	17.33	18.87	54.86
Mean	128.43	47.27	19.87	30.45
Range	72–175	17.33–70.41	2.3–50.69	8.3–54.8

Accelerometry data captured during each exercise was categorized as one of three outcomes: usable data, data with no pattern, or technological failure. The percentage of data corresponding to each outcome is provided below for each participant. Percentages were obtained by dividing the number of exercises included in the category by the total number of self-reported exercises over the 4-week period (i.e., # exercises with corresponding data/ total # self-reported exercise) and then averaging these values.

TABLE 2 | Comparison of self-report and accelerometer recorded duration.

	Total number of exercises used for analysis	Self-reported duration (s)	Total accelerometer-recorded duration (s)	Sum of accelerometer-recorded individual exercise set durations (s)	Difference of self-reported durations and accelerometer-recorded durations (s)	% Active time (Percent)	Difference of total exercise and sum of individual exercise set duration (s)
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
P1	74	416.44 (200.89)	403.11 (220.97)	248.45 (137.22)	15.60 (170.56)	63.99 (15.19)	220.59 (201.07)
P2	87	675.37 (473.08)	597.36 (453.76)	561.47 (451.76)	73.94 (175.35)	90.88 (7.89)	42.42 (50.25)
P3	109	262.99 (159.52)	262.07 (151.46)	223.91 (130.01)	−9 (49.31)	85.48 (10.81)	38.87 (45.37)
P4	31	761.25 (315.45)	604.90 (274.42)	430.43 (229.96)	182.29 (246.83)	76.55 (16.93)	210.5 (259.81)
P5	42	520.00 (401.63)	514.05 (406.50)	471.32 (370.64)	5.58 (53.60)	95.50 (3.84)	17.33 (13.15)
P6	90	718.82 (312.40)	670.52 (292.65)	599.43 (276.99)	55.09 (76.59)	92.77 (6.72)	45.23 (57.06)
P7	16	388.80 (189.83)	558.15 (363.77)	339.24 (222.16)	−154.23 (315.02)	91.37 (5.25)	26.58 (20.19)
Mean		534.81	515.74	410.61	24.77*	85.22	85.93
Range		262.99–761.25	262.07–670.52	223.91–599.43	−154.23 to 182.29	63.99–95.50	17.33–220.59

For each participant, self-reported exercise durations were obtained, and these values were averaged across all exercises. Accelerometry data was used to determine the duration of each exercise as well the sum of the duration of individual exercise sets. For each participant, the average exercise duration across all assigned exercises and the average of the sum of individual exercise set durations across all assigned exercises is provided below. The following calculations were completed for each exercise and then across all exercises for each participant. The percentage of active time was calculated as the ratio of sum of accelerometer-recorded individual exercise set durations/total accelerometer-recorded duration. The difference in self-reported total exercise duration and accelerometer-recorded total exercise duration was calculated as self-reported duration - total accelerometer-recorded duration. Similarly, the difference between exercise duration and the sum of individual exercise set durations was calculated as total accelerometer-recorded duration - sum of accelerometer-recorded individual exercise set durations.

**Mean of column 5 excluding P3 and P7: 66.5.*

Standard Deviation of Acceleration

When analyzing the graphs of individual exercise set average standard deviation of acceleration over time, the slopes of all trendlines associated with P2 and P6 ranged from −0.0005 to 0.0004 and represented minimal change in individual exercise set average standard deviation of acceleration over the length of the study period. For P3, seven of the nine slopes were positive (range: −0.0017 to 0.0117) and five of these corresponded to a statistically significant increase in the individual exercise set average standard deviation of acceleration over the study period ($p < 0.001$). See **Supplementary Figures 3–5** for graphs of these data and corresponding statistical analyses.

DISCUSSION

This paper presents the secondary analysis of data captured *via* a commercially available accelerometer during completion of an upper extremity home program for individuals with chronic stroke. Our analysis found that data captured *via* the accelerometer across all participants on average was

TABLE 3 | Comparison of individual exercise set and total exercise total average angular velocity (degrees/s) across all exercises.

	Total number of exercises for analysis	Individual exercise set angular velocities (A) Degrees/s Mean (SD)	Total exercise angular velocities (B) Degrees/s Mean (SD)	Angular velocity difference (A–B) Degrees/s
P1	74	159.01 (3.90)	107.18 (19.70)	51.83
P2	87	70.07 (7.4)	63.4 (4.13)	6.67
P3	109	161.74 (18.88)	136.73 (19.094)	25.01
P4	31	67.55 (1.56)	49.89 (3.37)	17.66
P5	42	71.08 (61.73)	68.79 (59.03)	2.29
P6	90	40.57 (11.70)	40.18 (10.38)	0.39
P7	16	45.32 (14.01)	44.14 (13.97)	1.18
Mean		87.91	72.89	15.02
Range		40.57–161.74	40.18–136.73	0.39–51.83

For each participant, accelerometry data was used to calculate the total average angular velocity within each individual exercise set. These values were averaged for each assigned exercise and then averaged over all assigned exercises for each participant (A). Similarly, accelerometry data was used to calculate total average angular velocity of the entire exercise (including rest breaks) for each assigned exercise and then averaged over all assigned exercises (B). The difference in these two variables was calculated (A–B) to understand how the inclusion and exclusion of rest breaks affects angular velocity.

missing more than half of the self-reported exercises. However, self-reported duration and duration as measured by the accelerometer were similar in exercises captured. In addition, total angular velocity matched anticipated differences between total exercise and individual exercise set values. Furthermore, angular velocity provided a measure of change across time, demonstrating an increase for all participants. The standard deviation of acceleration also demonstrated a change over time for one participant.

Data capture is an area of primary concern, particularly considering the amount of data loss in our investigation was almost twice the amount reported by Uswatte et al. (2006). Factors that could have contributed to the level of technological failure include the length of time data were captured unchecked and the loss of the Bluetooth connection between the phone and the devices. To support increased data capture, mechanisms to allow for data capture directly on the device or to have real time capture and uploading to an online server for daily monitoring could be beneficial (Lee et al., 2018). Research grade accelerometers have developed these features (ActiGraph, 2018), but accelerometers have not been reported as consistently used in clinical practice post-stroke (Donoso Brown and Fichter, 2017).

Despite the limited data capture, the available data were consistent with self-reported data. The greatest difference observed on average was ∼3 min when comparing self-reported and accelerometer-recorded duration. One explanation for the differences in self-reported and accelerometer-recorded duration could be the elapsed time between recording in the logbook and beginning the exercise. Our comparisons between accelerometer and self-reported data differ from previous research, which has often compared accelerometer outputs to standardized stroke assessments (Uswatte et al., 2006; Reiterer et al., 2008). These findings differ from a previous study which investigated reporting of daily paretic arm use to values captured *via* accelerometry and found that most participants either under or overreported their arm use in comparison to accelerometry measures (Waddell and Lang, 2018). One possible explanation for the difference between previous research and our study was that participants were directly recording practice in an individualized logbook, whereas previous investigations used a standardized self-reported assessment with a rating scale. This direct recording could have increased the accuracy between the self-reported and objective measure for data captured. Overall, having an objective report of time spent practicing could corroborate client report of practice and facilitate discussion about potential challenges. In addition, the ability to use total exercise duration and individual exercise set duration to calculate an active time percentage allows clinicians to understand more about how clients use breaks while engaging in home practice.

Our findings also suggest the potential for angular velocity and standard deviation of acceleration to monitor changes in practice. When graphed across time for the three participants with >50% data capture, the averages of individual exercise set total angular velocity indicated an increase in speed for all participants in at least two assigned exercises. This increase in speed would be anticipated as participants became more familiar with the exercises overtime. These findings suggest that the average of individual exercise set angular velocities could be valuable to clinicians in observing changes in practice. Additionally, the standard deviation of acceleration was able to capture a notable change for one participant. Another point of note was that neither of these variables appeared to change in a manner expected with the inclusion or removal of the intervention in the initial study (i.e., ABAB design). However, this finding is consistent with the results in the initial study as it did not demonstrate a consistent difference in adherence with the presence or absence of preferred music listening. Future investigations should continue to explore how best to use these variables for home practice and measurement of outcomes.

Limitations

There were several limitations to this secondary data analysis, including the limited diversity of the sample, selection of activities, potential error with data processing, and accuracy of self-reported data. Regarding the sample, all participants were in the chronic phase of stroke recovery; however, future investigations should include persons in the earlier phase of stroke recovery to allow for observation of change in variables like the standard deviation of acceleration. Exercises represented functional activities that occupational therapists would likely use as interventions for people post-stroke and were personalized to be motivating and relevant to each participant. Although these exercises allowed us to evaluate the use of accelerometers for real-life clinical activities; selection of other motor exercises that required different movements and positions of the upper extremity that were consistent across all participants may have allowed for more controlled data collection and precise analysis. Data processing contained many steps and future investigations would benefit from streamlining and automating many of these steps to allow for increased clinical utility and reduction of measurement error. For example, instead of visual inspection for start and stops, modifying the programming of the analysis program to identify these times based on minimum and maximum thresholds for angular velocity would decrease the time related to processing and reduce the influence of human error. Finally, while participants were trained to use the aphasia-friendly logbooks and competency was ensured prior to initiating independent practice, there is a potential for error and inaccuracies with collecting self-reported start and stop times. This error could impact how the .log files were initially cut during data processing, as well as comparisons made between self-reported and accelerometer-recorded duration.

Future Research

Future research can explore a variety of areas to further increase the potential of using commercially available accelerometers for home programs in research and clinical settings. First, cloud-based monitoring of accelerometer data during home exercise could potentially increase data capture and support real-time, technology-related problem solving. It would also be beneficial to compare the results of this study to a baseline study where exercises are performed in the presence of a rehabilitation therapist to mitigate data collection and technological errors. Additionally, machine learning could be investigated to increase the accessibility of clinically meaningful data for clients and rehabilitation therapists to receive feedback more easily. These potential areas of exploration (machine learning and cloud-based monitoring) would eliminate many technological issues and data processing steps, thus closing the gap between human-computer interaction challenges and margin of error.

In addition to refining the human computer interaction within the use of accelerometers for engaging in home programs, exploration of the utilization of these devices with virtual reality applications is an area for future investigations. Some initial explorations of combining accelerometry with virtual reality have used the accelerometer to monitor physical activity levels (Gomes et al., 2019), while others have aimed to create a device that can control objects in a virtual space (Perng et al., 2020). Findings from our study can support further integration into virtual reality applications by identifying variables of potential interest when monitoring practice remotely.

CONCLUSIONS

Our study specifically explored duration, angular velocity, and standard deviation of acceleration outputs, which can provide key feedback regarding practice times, quality of practice, and improvement in function over time during post-stroke rehabilitation programs. Overall, this study increases our understanding of how to interpret accelerometer output variables as clinically meaningful data during home exercise programs for post-stroke adults. Using commercially available accelerometers promotes the accessibility and affordability of accelerometers to be used in home environments, unlike related studies that often use research-grade devices. While the commercially available accelerometers produced data that aligned with the anticipated outcomes for the variables considered, challenges regarding the human-computer interaction between post-stroke adults and use of accelerometers must be overcome prior to implementation of this technology into real-world stroke rehabilitation programs. Additional research should be conducted to explore ways to increase data capture and expedite data processing. Ultimately, accelerometer data should be easily translated into information that is meaningful and motivating both to the client and rehabilitation therapists, as feedback is an important factor in the stroke rehabilitation process (Lee et al., 2018).

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Duquesne University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KD: primary person responsible for completion of secondary data processing and analysis, wrote first draft of entire paper, and major editing on paper submission. ED: co-PI on initial study, supported data processing and analysis, and major editing on paper submission. RM: lead developer of custom Matlab® software, supported data processing and analysis, and major editing. SW: co-PI on initial study and major editing on paper submission. 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/frvir.2021.642434/full#supplementary-material

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The Use of Embedded Context-Sensitive Attractors for Clinical Walking Test Guidance in Virtual Reality

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Virtual reality is increasingly used in rehabilitation and can provide additional motivation when working toward therapeutic goals. However, a particular problem for patients regards their ability to plan routes in unfamiliar environments. Therefore, the aim of this study was to explore how visual cues, namely embedded context-sensitive attractors, can guide attention and walking direction in VR, for clinical walking interventions. This study was designed using a butterfly as the embedded context-sensitive attractor, to guide participant locomotion around the clinical figure of eight walk test, to limit the use of verbal instructions. We investigated the effect of varying the number of attractors for figure of eight path following, and whether there are any negative impacts on perceived autonomy or workload. A total of 24 participants took part in the study and completed six attractor conditions in a counterbalanced order. They also experienced a control VE (no attractors) at the beginning and end of the protocol. Each VE condition lasted a duration of 1 min and manipulated the number of attractors to either singular or multiple alongside, the placement of turning markers (virtual trees) used to represent the cones used in clinical settings for the figure of eight walk test. Results suggested that embedded context-sensitive attractors can be used to guide walking direction, following a figure of eight in VR without impacting perceived autonomy, and workload. However, there appears to be a saturation point, with regards to effectiveness of attractors. Too few objects in a VE may reduce feelings of intrinsic motivation, and too many objects in a VE may reduce the effectiveness of attractors for guiding individuals along a figure of eight path. We conclude by indicating future research directions, for attractors and their use as a guide for walking direction.

Keywords: guidance, navigation, virtual reality, virtual environments, virtual rehabilitation, autonomy, self-determination theory, attractors

INTRODUCTION

Virtual Reality (VR) technology may be introduced into both clinical and community-based environments and has supported patients in a range of therapeutic activities. Examples include training for function led tasks (e.g., crossing a road, or shopping in a supermarket) (Corbetta et al., 2015; Dawson and Marcotte, 2017; Parsons et al., 2017), and construct led tasks, sometimes referred to as "exergames" (Dawson and Marcotte, 2017). Both function led, and construct led tasks can be managed safely (Fox et al., 2009; Borrego et al., 2016), and provide additional motivation in VR (Cikajlo et al., 2020), thus reducing patient boredom, increase patient motivation and compliance to engage with therapeutic activities (Chen et al., 2020). Although, VR supports a variety of different therapeutic activities, explicit instructions are often provided verbally to guide a patient through a task (Johnson et al., 2013; Jie et al., 2018; Mak et al., 2018; Kleynen et al., 2019). Information provided typically regards motor movement and technique performance (Denneman et al., 2018; Gokeler et al., 2019). However, this may increase reliance on declarative knowledge, increasing working memory due to patients having to remember and recall instructions and movement sequences (Buszard et al., 2017), and thus reduce movement automaticity (Denneman et al., 2018; Johnson et al., 2019). Implicit instructions can target these problems (Gokeler et al., 2019; Dahms et al., 2020), focus of implicit instructions in VR may be placed upon how a patient moves, often regarding the adaption of movement, based upon visual guidance (Anglin et al., 2017; Bonnette et al., 2020), for example, some applications have used biofeedback in conjunction with visual shape matching (Bonnette et al., 2020).

A particular challenge for patients when discharged to community-based environments is the ability to plan routes in unfamiliar environments, and partake in outdoor recreational activities (Palstam et al., 2019). This can lead to a decrease in social and familial interaction (Liu and Ng, 2019; Palstam et al., 2019), and thereby a decreased quality of life (Corbetta et al., 2015; Liu and Ng, 2019). Therefore, focus to address this problem could be placed upon introducing scenarios, that develop patient's route planning and anticipatory movements toward different simulated environments. Additionally, autonomy supported motivation may further support effective motor (re)learning (Wulf et al., 2015; Lemos et al., 2017). When a patient responds to controlled events, they might experience less autonomy, as their motivation is generated through controlled means (Keatley et al., 2013). A motivational theory which considers both controlled and autonomous motivation along a continuum is "Self-Determination Theory" (SDT) (Ryan and Deci, 2017). Within SDT there are three fundamental psychological needs including: autonomy, competence and relatedness (Ryan and Deci, 2017). When these needs are fulfilled, they may support patient confidence and may lead to an increase in physical activity (Sweet et al., 2012). Furthermore, it is important that the opportunities for patients to practice their decision making and anticipatory skills are developed within the safety of clinical environments (Johnson et al., 2013), ensuring that patients' skills are appropriately assessed by clinicians with regards to everyday functional tasks (Jie et al., 2018).

During everyday functional tasks, both curved and straight walking are utilized to navigate around obstacles in an environment (Schack et al., 2019). A widely-used walking intervention which assesses both straight and curved path walking is the "figure of eight walk test" (FO8WT) (Hess et al., 2010; Wong et al., 2013; Welch et al., 2016). However, if focus is placed upon patients' planning and anticipatory movements when implementing the FO8WT into VR, there needs to be balance between providing enough information to guide the patient along the figure of eight path whilst supporting autonomy to allow the patient to make their own navigational decisions. This raises the question of how the design of VR rehabilitation applications can accommodate the required information for the FO8WT through visual guidance mechanisms to complete relevant clinical activities/assessments, promote aspects of SDT (autonomy, competence, and relatedness), and reduce impact on working memory.

Visual guidance approaches such as manipulation of optic flow for example, increasing vection have previously been used to induce postural adjustments in individuals to alter the direction of navigation during walking (Furukawa et al., 2011). Similarly, redirected and reorientation techniques may make use of environmental and/or perspective manipulation to alter a user's path in both the virtual environment (VE) and the physical tracked space (Vasylevska et al., 2013; Nilsson et al., 2018). The manipulations introduced in extant literature have meant that users must compensate for differences between visual, vestibular, and somatosensory information to alter their walking direction, often without awareness (Vasylevska et al., 2013; Langbehn et al., 2017). Alongside visual manipulation approaches, haptic feedback can be used to induce changes in walking direction. One example, is the use of robotic guide dogs, who can help to guide the visually impaired safely along paths (Chuang et al., 2018), which may be implemented so that the user holds onto a cane/handle (Chuang et al., 2018), and when the robot turns the user receives haptic feedback based on the mass of the robot indicating movement (Hersh and Johnson, 2010). Another example is galvanic vestibular stimulation in which the placement of electrodes behind an individual's ear, can induce postural adjustments through the use of electrical currents (Maeda et al., 2005). Galvanic vestibular stimulation has been used to support reorientation techniques. For example, Sra (2017) made use of three different electrical current variations to elicit three different balance responses in order to influence walking direction (Sra, 2017). Even though these approaches have been shown to induce changes in walking directions, they require the user to compensate for any changes, and therefore in this context, it may be that these visual guidance mechanisms may not provide an appropriate level of autonomy.

If we wish to support navigational decisions and autonomy, we need to foster opportunities that can influence guidance, whilst reducing reliance on postural adjustment responses. Instead providing opportunities for individuals to respond as they would like, without negative consequences would appear particularly beneficial. Thus, an important consideration when designing visual guidance with the use of head-mounted display (HMD) VR applications is that the user can look freely around the VE. Consequently it is harder to visually guide their attention toward an intended direction (Grogorick et al., 2018). Whilst traditional visual guidance principles such as signs, maps, and continuous lines can be used in VR to aid in directing attention toward an intended area (Miller, 1992; Vilar et al., 2014), they can be obtrusive, and distracting from a given task (Grogorick et al., 2018). Therefore, subtle approaches to guidance can be considered, such as manipulation of light and artificial markers (e.g., colored dot) (Grogorick et al., 2018). However, for guidance purposes, current subtle approaches such as a colored dot may not appear natural within in a VE. Consequently, if a VR application is being used within the context of training applications these approaches should be used minimally, to ensure immersion remains high and increases the learning potential of an application (Lin et al., 2012; Cuperus et al., 2018; Grogorick et al., 2018).

VR based research areas such as cinematic VR, use visual saliency to attract attention (Nielsen et al., 2016), whilst redirected and reorientation techniques may make use of distractors as well as attractors in order to guide attention away from manipulations in a VE (Peck et al., 2009; Sra et al., 2018). Distractors used in redirected walking often gravitate toward explicit cues (Peck et al., 2009), where explicit cues are defined by Nielsen and collegaues (Nielsen et al., 2016), as using explicit communication to direct attention toward a certain object (Nielsen et al., 2016), for example with having to keep a distractor within their field of view, to aid unnoticeable rotational manipulations (Peck et al., 2009). Distractors may also be used in conjunction with audio only or a mixture of both visual and audio distractors, to guide navigation in a virtual environment (Rewkowski et al., 2019). In contrast attractors are often embedded into the design of a VE, and become the forefront for interaction within a VE (Sra et al., 2018). In particular embedded context-sensitive attractors are objects which are appropriate within a VE setting, which ensures that they are representative and designed with relation to the task and VE (Sra et al., 2018). However, current attractor approaches, in redirected walking techniques have been used in strict path following scenarios (Sra et al., 2018), and have not explored the design of attractors within autonomy based scenarios. Therefore, the primary aim of this study was to investigate how the design of embedded context-sensitive attractors may guide attention and walking direction in VR, during explorative walking, to invite the completion of the clinical FO8WT. The secondary aim was to ascertain whether the use of embedded context-sensitive attractors provided a sense of autonomy and minimized perceived workload in participants.

MATERIALS AND METHODS

We conducted a within-subjects experiment designed to examine the use of embedded context-sensitive attractors to convey instructions to walk a figure of eight path in a VE, when participants are given the opportunity to explore and of the effect of such attractors on perceived autonomy, and perceived workload. These studies were conducted at the University of Portsmouth (UK), and ethical approval was provided from the Faculty of Creative and Cultural Industries.

Context Embedded-Sensitive Attractor

To examine the effect of attractors and their effectiveness of providing information for completing the clinical FO8WT in VR, the participants were encouraged to explore the VR tracked space, making use of one-to-one mapping. The FO8WT may vary in length from 1.5 × 1.2 m (Hess et al., 2010), to the length of 10 m (Barnett et al., 2016). However, VR room-scale tracking spaces are ∼5 m (Langbehn et al., 2017). Therefore, it was decided that the representation of the FO8WT should be smaller than 5 m, but larger than 2 m in length to ensure continuity with other room-scale VR setups. Additional considerations include the assessment criteria in the FO8WT i.e., speed, amplitude (number of steps) and the accuracy of their turn (Hess et al., 2010; Odonkor et al., 2013; Barker et al., 2019). Therefore, elements used within the FO8WT such as cones (turning markers) should be considered when implementing the walk test into VR (Hess et al., 2010), being mindful that when represented in a VE, they make logical sense within the context of the setting. However, it is not known whether the use of turning markers will impact the guidance from the attractors. Therefore, turning markers will be present in some VE conditions and not others (**Figure 2**). Based on the application aiming to provide a sense of autonomy and using visual guidance mechanisms as instructions it was important to move away from architectural spaces and paths to reduce the number of confined paths within the VE (Bruder et al., 2013; Vasylevska et al., 2013; Nilsson et al., 2018). Therefore, in order to implement a VE that is not limited by confined paths, the present study made use of a natural environment—namely a forest—to overcome challenges of scale and shape in the VE, whereby the turning markers were replaced by trees. To, ensure similarity with the FO8WT though, participants started at the center of the FO8WT (Welch et al., 2016).

To ensure that the attractor was easily distinguishable within the VE, saliency properties including color, contrast, form, motion, location and size (Nielsen et al., 2016; Davis et al., 2017), were taken into consideration. Color is a saliency property which is considered relatively stable even with older populations (Davis et al., 2017), and objects which have complementary

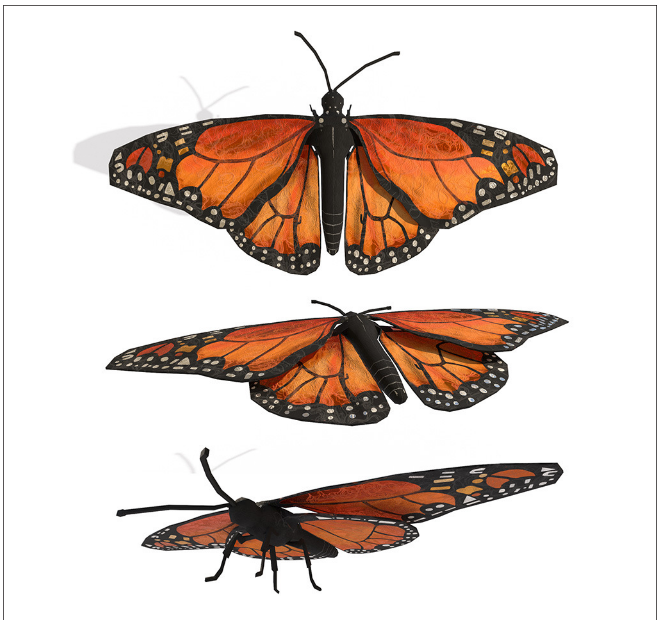

FIGURE 1 | Embedded context-sensitive attractor.

colors such as red and green are thought to be more noticeable (Thorpert et al., 2019). However, based on some types of color blindness, it is important to ensure that color is not the only saliency property. Moving objects are reported to attract large amounts of attention (Rothe and Hußmann, 2018; Yang et al., 2018), even in the absence of sounds (Rothe and Hußmann, 2018), and therefore, movement animation was added to the attractors.

To ensure that the attractor was representative of something found in a forest environment a "monarch butterfly" was chosen to represent the attractor(s) (**Figure 1**). The trees, and attractor were created using 3D Studio Max, and textured using Adobe Photoshop (Tree Material Reference Images (Textures.com, 2017a,b,c,d) and Substance Painter (hand-drawn texture for attractor). Due to the small size of the attractor, and the use of trees to represent turning markers in some conditions, it was

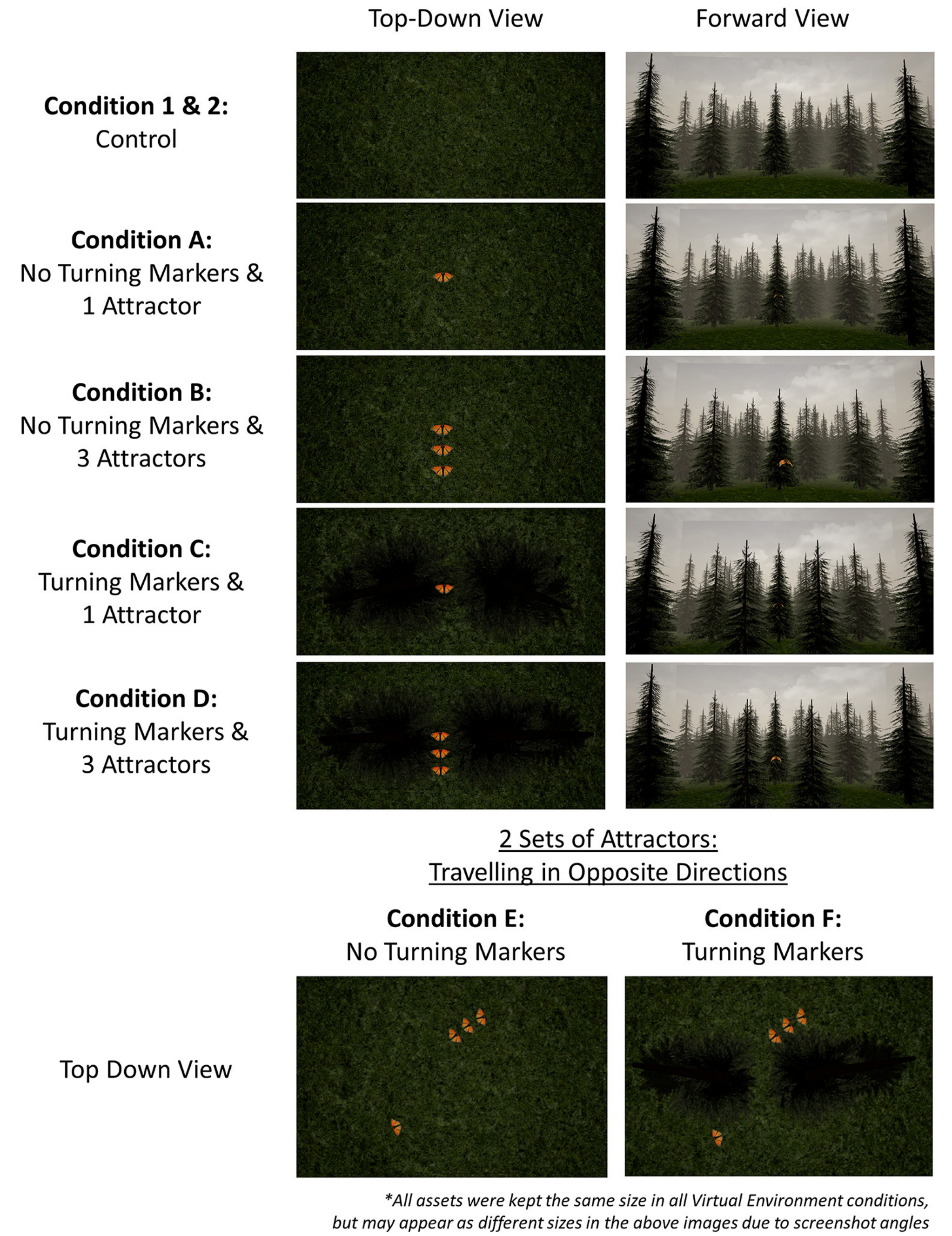

FIGURE 2 | Virtual environment conditions.

important to acknowledge that dependent on the attractor and participant location visibility to the attractor may be reduced. Therefore, the number of attractors used were altered from either 1–3 (**Figure 2**). In order to guide walking direction along a figure of eight path, the location of the attractor(s) responded dynamically to participants' position within the VE. The attractor(s) were programmed to move along the same pre-defined figure of eight path in each VE condition, but only when the participant was moving behind the attractor(s) and along the path in the correct direction. This was implemented with the use of a trigger box (not visible to participants) surrounding the attractors (which was the same size in all VE conditions, including when the attractors are not visible in the control conditions), in which the participants would trigger the attractors movement along the path, if they were behind the attractor(s) but still within the trigger box. The attractors would then move forward along the pre-defined figure of eight path until, the participants were no longer within the trigger box. Therefore, the speed of the attractors was not predefined but kept relative to the speed of the participants. Within eye movement literature, it is suggested that point of gaze is often kept slightly below the horizon line (Foulsham et al., 2011; Vansteenkiste et al., 2014; Tong et al., 2017). Therefore, the position of attractor(s) were kept just below the horizon line, at a height of 1.5 m.

Based upon the attractors introducing an affordance within the VEs, it was hypothesized that the use of attractor(s) will lead to a significant difference in participants following the figure of eight path, when compared to no attractor(s). The implementation of turning markers and increased amount of attractors, were design decisions to ascertain whether they had any impact on guidance, perceived autonomy and perceived workload.

Two Sets of Embedded Context-Sensitive Attractor

Two additional conditions were added to investigate whether participants would always follow the same set of attractors, when presented with two different sets of attractors (1 or 3 Attractors) which moved at the same time in the opposite direction of the figure of eight path (**Figure 2**).

Participants

Twenty-four Participants (11 Male, 13 Female) aged 21–65 (M = 34.25, SD = 11.29) were recruited from staff and students at the University of Portsmouth, and via word of mouth. All participants completed the experiment and were naïve to all experimental conditions. They did not receive any compensation for taking part in the study. The total duration of the study for each participant was ∼1 h.

Procedure

Participants were briefed on the procedure and safety of the study. Once consent was obtained, participants completed a demographics questionnaire (**Table 1**).

TABLE 1 | Demographics questionnaire results.

Statement topic	Scale	Results
Familiarity with VR Participants: 14/24	1 (Very unfamiliar) – 5 (Very familiar)	Mdn = 3.5 SD = 1.47
Duration of playing video games Participants: 13/24	1 (Under 1 h), 2 (1–3 h) 3 (3–5 h), 4 (5+ h)	Mdn = 2 SD = 0.49
Frequency of playing video games Participants: 13/24	1 (Very infrequent) – 5 (Very frequent)	Mdn = 3 SD = 1.47

The participants were informed that there were different VEs within this study, and that the researchers would be unable to respond to any questions during the experiment. Their task in each VE remained the same in which they were free to explore the VEs so long as they stayed within the tracked space. Participants were directed to the starting location, indicated by a cross on the floor (**Figure 3**), and instructed for that VE (which remained the same for each VE) "you have one minute to walk wherever you like, without walking outside of the blue cage, which is for your safety."

Each participant experienced the attractors based VE conditions in a counter-balanced order, with the control conditions (no attractor and no turning markers), being present both at the very beginning and end of the study. In each condition, participants were given 1 min to explore the VE. The chosen duration of 1 min has been used in a similar assessment of dynamic balance when walking along a FO8 path (Gil-Gómez et al., 2011). In between each VE condition, the participants answered questionnaires, whilst they were seated without the HMD.

The VEs were loaded by the researcher in the pre-defined sequence for each participant once the participants were standing on the starting position and facing the correct direction. The VE faded to black for the 10 s at the beginning of each condition, as an adjustment period for each participant.

Apparatus

The study took place in an 8 × 8 m laboratory, with a 4 × 4m tracked space. All objects were kept securely out of the way, and any wires were taped down around the edge of the room. Participants wore the HTC vive 2016 HMD for ∼10 min altogether and were instructed to take breaks if needed. For participant safety, the HTC vive guardian boundary was included and appeared when the participant moved toward the edge of the $4m^2$ tracked area, this was referred to as the "blue cage" when talking to participants. Positional data (X, Y, and Z) from the HMD was recorded from the HTC vive lighthouses® continuously at 6 hz. The VE conditions were designed to be symmetrical, in both the X and Y axis, in order not to introduce directional bias and were rendered in real time using Unreal Engine 4.14.

Dependent Variables

Participant and attractor(s) trajectories were recorded in cm by measuring the x and y co-ordinates of every 10th of a second, with the participants location was recorded from the position of the HMD. The distance in which participants followed the figure

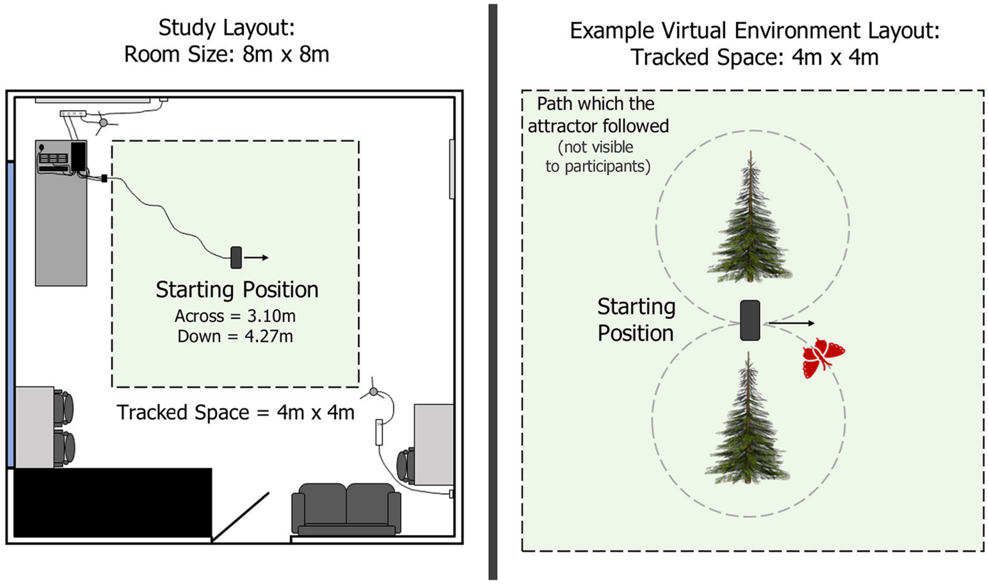

FIGURE 3 | Room and example virtual environment layouts.

of eight path was calculated taking the sum of the Euclidean distances calculated from the attractor coordinates. To analyze whether participants followed one particular set of attractors over the other (1 or 3 attractors), the sum of total time followed in seconds was computed. Calculated by taking the smallest Euclidean distance between the participants to the moving attractors indicating whether the participant was following the set with 1 attractor or 3 attractors. Euclidean distance was also used to calculate the largest distance a participant deviated away from the attractor(s).

Self-determination was measured using the 22 statement task evaluation questionnaire (Self-Determination, 2020), which is a subset of the intrinsic motivation inventory (IMI) (Ryan, 1982; Deci et al., 1994). There are four subscales that make up the task evaluation questionnaire including: interest and enjoyment (considered a subscale of intrinsic motivation), perceived competence, perceived choice and pressure/tension (considered as a negative predictor of intrinsic motivation) (Deci et al., 1994). The ending of statement 7 was altered from "I think I did pretty well at this activity, compared to other students" "…to other participants." Although, each participant would have been the only person currently undertaking the activity of exploring the VE they were asked to make their own judgement of how well they think they did. This statement is used in the calculation of perceived competence (Deci et al., 1994), this subscale needs to be analyzed with consideration that they were naïve to experimental conditions, and were the only people taking part in the experiment at a given time. Therefore, analysis focused upon whether they felt there was any difference within the conditions.

The modified NASA—Task Load Index (NASA-TLX) was used to measure perceived workload (Hart, 2006; Bustamante and Spain, 2008). The chosen approach to using the NASA-TLX was to use the shorter version, as the weighted version can be time consuming (Hart, 2006; Bustamante and Spain, 2008), and may introduce participant errors (Bustamante and Spain, 2008).

RESULTS

There were two participants with tracking issues regarding the first control condition only. One participant had an HMD tracking error, in which they had a fixed offset of −94 on the x axis, for the first control only. Although the participant trajectory can be easily translated, due to the implementation of the attractors correspondence along the figure of eight path raises concerns over accuracy. In addition, another participant completely lost tracking data. Therefore, both participants were excluded from trajectory-based data analysis, for the following variables: following of the attractor(s) and largest distance away from attractor(s), but not the two sets of attractors as this analysis was separate from the control conditions. All statistical analysis used a 95% confidence interval, unless otherwise stated.

Following of Embedded Context-Sensitive Attractor

The total distance in cm, that the participant followed the attractor(s) was not normally distributed at the 5% confidence interval level. Therefore, the non-parametric Friedman Test was used to compare the distance in cm, that the participant followed the attractor(s), in the control (averaged between the control at the beginning and end of the study), compared to the other VE attractor conditions. There was a significant difference $X^2_{(4)} = 15.72$, $p = 0.003$, with regards to the total distance participants followed the attractor and the VE attractor conditions. *Post-hoc* analysis with the Wilcoxon signed-rank test were conducted with

TABLE 2 | Wilcoxon signed-rank test—distance spent following the attractor.

Pairing	Median	Quartiles	*Z* val.	*P* val.	*r*
Control A	79.55 502.93	41.50–149.53 101.32–2031.20	−3.62	< 0.000*	0.77
Control B	79.55 276.74	41.50–149.53 190.53–1219.20	−3.75	< 0.000*	0.80
Control C	79.55 367.55	41.50–149.53 92.97–954.23	−3.00	0.003*	0.64
Control D	79.55 165.96	41.50–149.53 45.26–649.57	−2.13	0.03	0.45
A B	502.93 276.74	101.32–2031.20 190.53–1219.20	−1.19	0.24	0.25
A C	502.93 367.55	101.32–2031.20 92.97–954.23	−1.70	0.09	0.36
A D	502.93 165.96	101.32–2031.20 45.26–649.57	−1.77	0.08	0.38
C B	367.55 276.74	92.97–954.23 190.53–1219.20	−0.44	0.66	0.09
D B	165.96 276.74	45.26–649.57 190.53–1219.20	−0.93	0.36	0.20
D C	165.96 367.55	45.26–649.57 92.97–954.23	−1.03	0.31	0.22

Control, Averaged values from the 1st and 2nd control; A, No Turning Markers and 1 Attractor; B, No Turning Markers and 3 Attractors; C, Turning Markers and 1 Attractor; D, Turning Markers and 3 Attractors. **significant value at $p < 0.005$.*

a Bonferroni correction applied, resulting in a significance level set at $p < 0.005$, there were 3 significant pairings (**Table 2**).

On visual observation of participant trajectories, some participants did not appear to follow the attractor once it was introduced but may still make both clockwise and anticlockwise turnings (**Figure 4**).

The largest distance away from the attractor(s) in cm, was not normally distributed at the 5% confidence interval level. Therefore, the non-parametric Friedman Test was used. There was a significant difference $X^2_{(4)} = 15.49$, $p = 0.004$, with regards to the largest deviation away from the attractor and the VE attractor conditions. *Post-hoc* analysis with the Wilcoxon signed-rank test were conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.005$, there were 3 significant pairings (**Table 3**).

Two Sets of Attractors

The total time in seconds, that the participants followed one set of attractors were not normally distributed at the 5% confidence interval level. Therefore, the results were analyzed using the non-parametric Friedman test to compare the time spent following one set of attractors (1 or 3 attractors) and the placement of turning markers in seconds. There was not a significant difference $X^2_{(3)} = 2.81$, $p = 0.42$ (**Table 4**).

Task-Evaluation Questionnaire

One participant was removed from statistical analysis within the task-evaluation questionnaire statistics as they had not completed all forms.

The non-parametric Friedman test was used to compare all the task-evaluation variables. There was a significant difference between the use of attractors and turning markers and the perceived interest and enjoyment scores (a measure of intrinsic motivation) $X^2_{(6)} = 31.56$, $p < 0.000$. *Post-hoc* analysis with the Wilcoxon signed rank test were conducted with a Bonferroni correction applied, resulting in a significance level of $p < 0.005$, there were 5 statistically significant pairings (**Table 5**).

There was a significant difference between the use of attractors and turning markers and the perceived "Pressure/Tension" (negative predictor of intrinsic motivation) scores $X^2_{(6)} = 23.52$, $p = 0.001$. *Post-hoc* analysis with the Wilcoxon signed rank test were conducted with a Bonferroni correction applied, resulting in a significance level of $p < 0.005$, there were 2 statistically significant pairings (**Table 6**).

There was not a significant difference between the use of attractors and turning markers and the perceived competence scores $X^2_{(6)} = 5.81$, $p = 0.45$. Along with no significant difference between the use of attractors and turning markers, and the perceived choice scores $X^2_{(6)} = 8.28$, $p = 0.22$ (**Table 7**).

NASA-TLX

The NASA-TLX results from all conditions were analyzed using the non-parametric Friedman Test and there was no statistical difference between any of the VE attractor conditions and the NASA-TLX variables (Mental Demand: $X^2_{(6)} = 10.64$, $p = 0.10$, Physical Demand: $X^2_{(6)} = 4.81$, $p = 0.57$, Temporal Demand: $X^2_{(6)} = 4.59$, $p = 0.60$, Performance: $X^2_{(6)} = 6.22$, $p = 0.40$, Effort: $X^2_{(6)} = 7.98$, $p = 0.24$, Frustration: $X^2_{(6)} = 5.63$, $p = 0.47$, Overall: $X^2_{(6)} = 5.15$, $p = 0.52$) (**Table 8**).

DISCUSSION

This study explored how the use of visual attractors can be implemented for guidance in completing the clinical FO8WT, whilst keeping verbal instructions minimal. In addition, it examined whether the use of attractors in VEs can negatively impact perceived autonomy and workload. The results from this study indicate that, even when a verbal instruction encourages exploration, the use of attractors can guide walking direction with participants following an implied figure of eight path. This may be due to the implementation of the attractors, in which there is an action and feedback loop provided to participants. Where movement of the attractors along a predefined figure of eight path, occurs if the participant is behind the attractors and within a trigger box (not visible to participants), thus providing a (perceived) affordance for the participants within the VEs (Norman, 1999; Lee et al., 2018). There was also a reduced distance away from the implied path with the introduction of the attractor(s). The use of attractors being effective at supporting guidance for where to move, aligns with existing literature in which visual guidance mechanisms have previously been used to support implicit motor (re)learning, and have focused upon how to move (Anglin et al., 2017; Baird and Stewart, 2018; Bonnette et al., 2020).

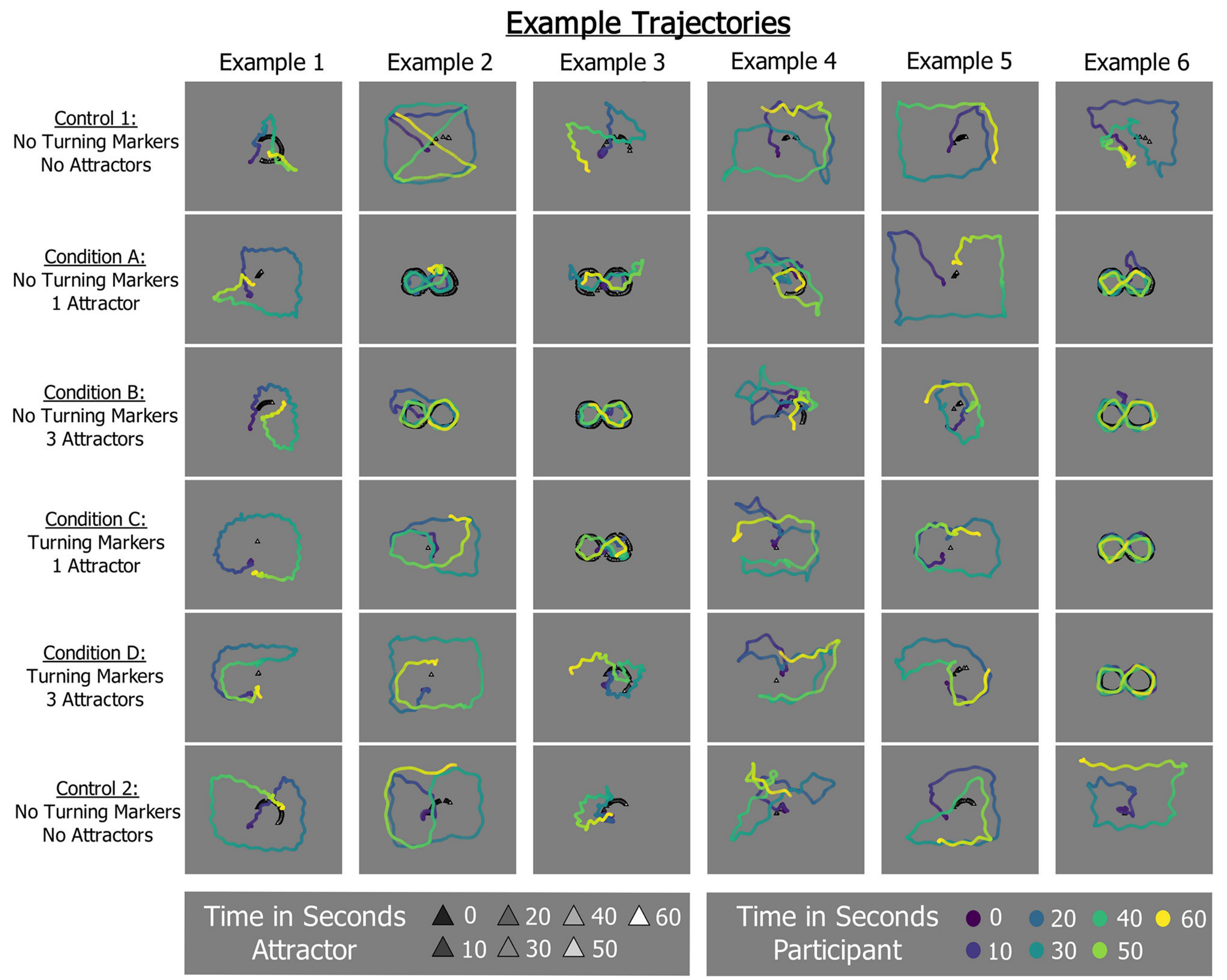

FIGURE 4 | Example participant trajectories from each group—minus conditions E & F.

Although the attractors were found to be beneficial at guiding participants along a figure of eight path, condition D (Turning markers and 3 attractors) did not significantly differ from the average control (no attractors or turning markers). Upon observation of the participant trajectories there are some emergent patterns. Some participants appear to always follow the attractor; however, there were other participants who decreased in following the attractor when more attractors and turning markers were introduced.

This observation appears to suggest that an increase in objects in a VE may impact the effectiveness of guidance. The reason for this occurrence, may be visual crowding, as objects may become more difficult to differentiate (Whitney and Levi, 2011; Henry and Kohn, 2020). This is often as a result of attention and spatial integration (Henry and Kohn, 2020), in which the distance between objects in an environment are crucial for being able to identify a target object (Bouma, 1970; Whitney and Levi, 2011; Melnik et al., 2020). Although this study did not infer the attractors as a target object, participants may have identified this as a target object within the VE, however visual crowding may have occurred when placing more objects into the VE, making it more difficult to identify the attractors as a target object.

Alternative to the theory of visual crowding (Bouma, 1970), Schmitz and colleagues (Schmitz et al., 2020) suggest that individuals may become desensitized to visual cues, due to constant stimulation. However, it is perhaps unlikely that this explains why following of the implied path in condition D (turning markers and 3 attractors) did not significantly differ from the average control (no attractors or turning markers), as participants only experienced all attractor conditions for a total of 6 min, in a counter-balanced order. This raises important questions as to whether there are saturation points of attractors and other visual methods when guiding attention.

The secondary aim of this study was to ascertain whether the use of attractors provided a sense of autonomy and minimized the impact of perceived workload in participants.

TABLE 3 | Wilcoxon signed-rank test—largest distance away from attractor.

Pairing	Median	Quartiles	Z val.	P val.	r
Control A	275.92 184.56	237.95–297.95 103.07–235.35	−3.26	0.001*	0.70
Control B	275.92 170.99	237.95–297.95 106.44–251.80	−2.97	0.003*	0.63
Control C	275.92 215.74	237.95–297.95 159.53–246.81	−3.33	0.001*	0.71
Control D	275.92 224.51	237.95–297.95 161.66–252.33	−2.65	0.008	0.56
A B	184.56 170.99	103.07–235.35 106.44–251.80	−0.15	0.88	0.03
A C	184.56 215.74	103.07–235.35 159.53–246.81	−1.38	0.17	0.29
A D	184.56 224.51	103.07–235.35 161.66–252.33	−1.22	0.22	0.26
C B	215.74 170.99	159.53–246.81 106.44–251.80	−1.38	0.17	0.29
D B	224.51 170.99	161.66–252.33 106.44–251.80	−0.50	0.62	0.11
D C	224.51 215.74	161.66–252.33 159.53–246.81	−0.05	0.96	0.01

*Control, Averaged values from the 1st and 2nd control; A, No Turning Markers and 1 Attractor; B, No Turning Markers and 3 Attractors; C, Turning Markers and 1 Attractor; D, Turning Markers and 3 Attractors. *significant value at $p < 0.005$.*

TABLE 4 | Time spent following specific attractor set in seconds.

Time spent following	Median	Q1	Q3
Condition E−1 Attractor	4.15	0.98	8.65
Condition E−3 Attractors	4.05	1.33	10.05
Condition F−1 Attractor	3.15	0.60	6.33
Condition F−3 Attractors	2.80	0.80	5.80

Condition E, No Turning Markers; Condition F, Turning Markers.

Although this study was conducted with adults that were not undergoing rehabilitation, the results indicated that not only did the design of attractors provide guidance for following an implied figure of eight path but do not negatively impact perceived choice (range 6.7–7) or workload (reported low to medium). The use of attractors was able to provide additional interest and enjoyment results (considered a subscale of intrinsic motivation), when compared to the control (except for condition A). This aligns with other work suggesting that simple scenes can convey information (Nielsen et al., 2016) but that open world environments provide more enjoyment (Ijaz et al., 2020). Furthermore, condition F (2 sets of attractors and turning markers) was perceived to have less pressure/tension than both the control and condition E (2 sets of attractors and no turning markers). Although these were significant differences, it is important to consider that these values were still mid to high for interest and enjoyment and low for pressure and tension. This is a beneficial aspect of the design of attractors,

TABLE 5 | Wilcoxon signed-rank test—interest and enjoyment scores.

Pairing	Median	Quartiles	Z val.	P val.	r
Control A	4.93 5.14	4.15–6.15 4.43–6.57	−2.00	0.05	0.42
Control B	4.93 5.14	4.15–6.15 4.71–6.58	−2.99	0.003*	0.62
Control C	4.93 5.57	4.15–6.15 4.14–6.71	−2.87	0.004*	0.60
Control D	4.93 6.00	4.15–6.15 4.57–6.86	−3.46	0.001*	0.72
Control E	4.93 5.86	4.15–6.15 5.14–6.86	−3.26	0.001*	0.68
Control F	4.93 5.71	4.15–6.15 4.29–6.86	−2.83	0.005*	0.59
A B	5.14 5.14	4.43–6.57 4.71–6.58	1.03	0.30	0.21
A C	5.14 5.57	4.43–6.57 4.14–6.71	1.60	0.11	0.33
D B	6.00 5.14	4.57–6.86 4.71–6.58	−1.02	0.31	0.21
D C	6.00 5.57	4.57–6.86 4.14–6.71	−1.29	0.20	0.27
F E	5.71 5.86	4.29–6.86 5.14–6.86	0.03	0.98	0.01

*Control, Averaged values from the 1st and 2nd control; A, No Turning Markers and 1 Attractor; B, No Turning Markers and 3 Attractors; C, Turning Markers and 1 Attractor; D, Turning Markers and 3 Attractors; E, No Turning Markers−2 sets of Attractors; F, Turning Markers−2 Sets of Attractors. *significant value at $p < 0.005$.*

TABLE 6 | Wilcoxon signed-rank test—pressure/tension scores.

Pairing	Median	Quartiles	Z val.	P val.	r
Control A	1.60 1.20	1.30–2.60 1.00–3.00	−0.26	0.82	0.05
Control B	1.60 1.60	1.30–2.60 1.00–2.80	−0.98	0.33	0.20
Control C	1.60 1.20	1.30–2.60 1.00–2.40	−1.29	0.20	0.27
Control D	1.60 1.20	1.30–2.60 1.00–2.40	−0.92	0.36	0.19
Control E	1.60 2.20	1.30–2.60 2.20–2.20	−1.48	0.14	0.31
Control F	1.60 1.00	1.30–2.60 1.00–1.20	−3.13	0.002*	0.65
A B	1.20 1.60	1.00–3.00 1.00–2.80	0.44	0.66	0.09
A C	1.20 1.20	1.00–3.00 1.00–2.40	0.74	0.46	0.15
D B	1.20 1.60	1.00–2.40 1.00–2.80	−1.09	0.27	0.23
D C	1.20 1.20	1.00–2.40 1.00–2.40	−0.20	0.84	0.04
F E	1.00 2.20	1.00–1.20 2.20–2.20	−3.74	0.000*	0.78

*Control, Averaged values from the 1st and 2nd control; A, No Turning Markers and 1 Attractor; B, No Turning Markers and 3 Attractors; C, Turning Markers and 1 Attractor; D, Turning Markers and 3 Attractors; E, No Turning Markers−2 sets of Attractors; F, Turning Markers−2 Sets of Attractors. *significant value at $p < 0.005$.*

as intrinsic motivation may impact learning as a result of the individual behaving in a certain way because they desire to Ryan and Deci (2020). Therefore, it would be interesting to explore the use of attractors in the context of rehabilitation.

Ntoumanis et al. (2020) suggest that self-determination interventions in healthcare could be used to target autonomy, competence and relatedness at different intensity levels. Self-determination was measured in relation to design decisions, of both attractors and turning markers. Even though perceived competence did not significantly differ, in this study were the only individuals participating in the experiment at a given time and were required to be able to walk and stand without difficulty for 1-h. Therefore, in the context of rehabilitation attractors may elicit different perceived competence results, and future research will be needed to explore this further. Therefore, using attractors for guidance to complete clincal tests such as the FO8WT may be best used as an autonomy supportive intervention. Future research could explore, the use of attractors within the context of the FO8WT, but with focus placed upon how a patient moves, along with how they approach each aspect of the FO8WT (e.g., clockwise and anti-clockwise turns). This is particularly important as both curved, and straight walking are utilized in everyday walking (Schack et al., 2019), and require patients to use different muscles (Hess et al., 2010; Wong et al., 2013). This may interlink with research that considers patient confidence regarding their own motor capability, which is argued to interlink with patient motivation and continued recovery (Morris et al., 2017), and whether this may then impact how therapists target different patients motor (re)learning.

Additionally, even though this study had no significant statistical differences for preference of following a specific set of attractors in the two VE conditions where two attractor sets present (condition E and F), future research could explore differences between personal preferences and presenting two different types of attractors and the effect that this may have on guidance within a VE. As personal preference interlinks with the idea of enjoyment, it may explain the reason as to some of the observed behaviors such as participants avoiding the attractor, or always following the attractor regardless of other environmental aspects. Although it was not measured in the study, some of the participants stated that they disliked insects and therefore did not try to follow the butterflies whilst the opposite was true for other participants.

The overall results and observations from this study indicate that attractors can be used as guidance for completing a clinical FO8WT whilst allowing feelings of intrinsic motivation and decision-making opportunities. Although this study was conducted with a non-clinical group of participants, it is

TABLE 7 | Perceived competence and perceived choice—medians and quartile values.

Condition	Perceived competence median and quartiles	Perceived choice median and quartiles
Condition A	5.00 (4.00–6.00)	6.80 (6.40–7.00)
Condition B	4.80 (4.20–6.20)	6.80 (6.40–7.00)
Condition C	5.00 (4.40–6.00)	6.80 (6.60–7.00)
Condition D	5.00 (4.00–6.00)	6.80 (6.40–7.00)
Condition E	4.80 (4.00–6.20)	6.80 (6.20–7.00)
Condition F	5.00 (4.20–6.20)	7.00 (6.40–7.00)
Average Control	4.70 (4.10–5.70)	6.70 (6.20–7.00)

Control, Averaged values from the 1st and 2nd control; A, No Turning Markers and 1 Attractor; B, No Turning Markers and 3 Attractors; C, Turning Markers and 1 Attractor; D, Turning Markers and 3 Attractors; E, No Turning Markers—2 sets of Attractors; F, Turning Markers—2 Sets of Attractors.

TABLE 8 | NASA-TLX results.

	NASA–TLX subscale results						
	A Mdn, Q1 and 3	**B** Mdn, Q1 and 3	**C** Mdn, Q1 and 3	**D** Mdn, Q1 and 3	**E** Mdn, Q1 and 3	**F** Mdn, Q1 and 3	**Ave.** Mdn, Q1 and 3
MD	15 6.25–30	15 6.25–35	20 6.25–30	20 10–30	20 10–33.75	20 11.25–28.75	15 8.13–20
PD	15 6.25–27.5	12.50 6.25–30	15 6.25–25	15 10–23.75	15 10–28.75	15 10–23.75	15 10–19.38
TD	12.5 5–28.75	15 6.25–33.75	15 6.25–25	15 10–28.75	15 6.25–28.75	15 5–30	12.5 7.5–21.25
P	30 15–50	20 10–48.75	22.5 15–50	25 10–43.75	25 11.25–50	20 10–48.75	31.25 15.63–47.5
Effort	15 6.25–25	15 6.25–25	15 6.25–23.75	15 10–23.75	15 10–25	15 6.25–25	12.5 5.63–21.88
Frustration	10 5–18.75	10 5–20	10 5–13.75	10 5–28.75	7.5 5–23.75	10 5–15	10 5–25.63
Overall	17.5 10.21–27.71	19.17 12.71–25.21	17.5 11.88–24.17	16.67 12.83–29.17	18.34 12.71–26.67	15.83 11.88–26.25	15.42 11.67–23.12

Ave., Averaged values from the 1st and 2nd control; A, No Turning Markers and 1 Attractor; B, No Turning Markers and 3 Attractors; C, Turning Markers and 1 Attractor; D, Turning Markers and 3 Attractors; E, No Turning Markers and 2 sets of Attractors; F, Turning Markers and 2 sets of Attractors.
MD, Mental Demand; PD, Physical Demand; TD, Temporal Demand; P, Performance; Overall, Overall Cognitive Demand.

important to be mindful when using attractors in clinical settings, to consider the overall design of a VE. Insufficient attractors and additional environment objects may reduce feelings of intrinsic motivation or may become less effective for walking direction guidance. Both were observed in condition A (no turning markers and 1 attractor) and D (turning markers and 3 attractors). Furthermore, it is important to consider when implementing turning markers, the effects this may have on the tightness of turns from participants. For example, fir trees were used to represent turning markers in this application, but trees that are smaller or larger may provide different control with regards to size of turning circles. Furthermore, patient preference may interfere with the effectiveness of guidance so different ecologically valid attractors should be considered. However, it is important to be mindful of visual crowding and saliency as this can cause objects to appear similar (Melnik et al., 2020) and possibly decrease the effectiveness of the attractors. Therefore, we suggest that future research should explore (a) the effectiveness of attractors as instructions, alongside aspects of personal preference and saturation of interest, (b) the impact attractors have on how someone moves, both inside and outside of rehabilitation settings.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Portsmouth Faculty of Creative and Cultural Industries. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

The experiment was designed and conceptualized by CC, BS, and VP. The data acquisition was conducted by CC. Formal analysis was conducted by CC with statistical advice provided from MD. Supervision for this study was completed by WP, MD, BS, and VP. The author who took lead on writing the manuscript was CC and main feedback with edits were provided by WP. All authors contributed feedback to the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.621965/full#supplementary-material

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frontiers in Virtual Reality

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Visual Capture of a Tactile Sensation is Influenced by Repeated, Structured Exposure of a Visual Stimulus in Virtual Reality

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Phantom limb pain is commonly known as a neurological condition, where an amputee will continue to feel a limb that is no longer present in a painful fashion. Virtual mirror therapy (VMT) has been suggested as a method for alleviating phantom limb pain. The inclusion of tactile sensation in VMT has shown to be beneficial; however, delivering a tactile sensation to a phantom limb, without the use of invasive procedures, can be difficult. The current approach for transferring a tactile sensation to a phantom limb is called visual capture. The ability to establish visual capture has been demonstrated in VMT applications. However, there is little research into whether an established visual capture effect can be relocated to a more distal location for phantom limb pain management. This paper investigates whether a passive vibrotactile sensation can be moved to a distal location from its veridical location using a series of distally located lights presented in either a random or a structured fashion. Eight non-amputee participants were tasked with localising a static tactile sensation on a virtual arm. These vibrotactile sensations were presented simultaneously with a visual light stimulus, either co-located or located distally at three different locations. Findings show that a tactile sensation without a visual stimulus was difficult for participants to localise; however, when a visual stimulus was added, they were better able to locate the veridical tactile position. The structured group exhibited a larger range of tactile relocation responses than the random group. However, this result was unreliable, with the majority of the responses situated at the vibrotactile actuator. There was a significant difference between the random and structured group's ability to retain a visual capture at the veridical vibrotactile location when the lights were located distally. The random group did not express a visual capture response when the lights were presented distally while the structured group did, suggesting the structured group developed a more robust association between the visual stimulus and the vibrotactile stimulus. Findings may be of use where increasing tactile acuity without significant alteration of a veridical location is a desired therapeutic outcome.

Keywords: Visuo-tactile, Multisensory, Virtual reality, Phantom limb pain, Rehabilitation, Visual capture, Tactile localisation, Tactile acuity

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1 INTRODUCTION

1.1 Phantom Limb Pain, Visual Capture-Based Rehabilitation and Neural Plasticity

Phantom limb pain (PLP) is a specific type of deafferentation pain which affects amputees. It is a neurological condition where a person will continue to feel a painful limb even if it is no longer there. The phantom limb will generally experience cramping, itching, freezing, or burning temperatures (Weeks et al., 2010). Similar symptoms have been expressed without loss of limb such as brachial plexus avulsion or stroke in which injury or damage is sustained in the brain (somatosensory cortex and motor) or peripheral nerves (Shankar et al., 2015). Deafferentation and phantom limb pain have been shown to be very complex, and effective treatment remains undecided due to low-level evidence in findings (Dunn et al., 2017). Cognitive treatments such as mirror box therapy have shown to be promising and small-scale studies have shown to have good efficacy for managing pain without the possible side effects that invasive or pharmacological treatments have presented (Richardson and Kulkarni, 2017).

Traditional mirror box therapy visually superimposes a reflection of their intact limb onto their phantom limb, using mirrors. The mechanism utilised by mirror box therapy is a psychological principle called visual capture, sensory calibration, or the ventriloquism effect, and takes advantage of human's natural tendency to rely on visual cues over other modalities (Carey et al., 2019). If a non-visual stimulus is presented simultaneously and in a congruent manner with a visual stimulus, the visual stimulus will generally capture properties of the other modality, such as positional information. This visual illusion allows a clinician to remedy the pain in their phantom limb by manipulating or stimulating their intact limb, even though the phantom limb is not directly accessible (Carey et al., 2019). The current understanding for the emergence of phantom limb pain and the approach to treatment, is the brains natural plasticity and reorganisation after injury and amputation Flor and Diers (2009). Thus, the goal of mirror therapy is to stimulate affected areas of the brain such as the motor cortex and the somatosensory cortex via the intact limb or representation of the affected limb. Stimulation in the motor and somatosensory cortex is stated to reverse or alleviate the structural neural reorganisation that takes place in amputees or patients suffering from deafferentation pain (Flor and Diers, 2009; Kuner and Flor, 2017).

Cognitive treatments have been augmented from analogue means using mirrors to a more technological means using virtual reality or augmented reality. Virtual mirror therapy (VMT) aims to recreate the lost or deafferented limb in a virtual environment using head mounted displays or desktop monitors. This is accomplished by either reflecting the intact limb using hand trackers such as motion capture equipment or extending virtually recreating the limb using myoelectric sensors, which take the small electrical efferent signals in the in residual limb or adjacent muscles to drive the movements of the virtual limb (Ortiz-Catalan et al., 2014; Wake et al., 2015; Sano et al., 2016). This translation to more technological means allows more tailored experiences, which have resolved some of the issues faced in traditional forms, such as the ability to customise the appearance of the limb for better embodiment, or to extend the virtual limb using the residual limb in the case of bilateral amputees (Dunn et al., 2017; Perry et al., 2018). Akin to traditional methods, the effectiveness of virtual mirror therapy has shown to increase with the inclusion of additional modalities (Wake et al., 2015; Sano et al., 2016; Osumi et al., 2020).

1.2 Virtual Mirror Therapy Utilising Visuo-Tactile Methods

Application of virtual mirror therapy has focused on visualisation of the limb and creating proprioceptive exercises to alleviate cramping and postural issues, however, these sensations constitute only a portion of the painful experience's amputees suffer from (Pirowska et al., 2014). Burning, freezing, shooting pain and other paraesthesia are prevalent experiences associated with deafferentation pain and phantom limb pain and findings suggest that these painful phenomena are not as well managed by proprioceptive based exercises such as virtual mirror therapy (Osumi et al., 2019). This may be due to paraesthesia generally relating to the somatosensory cortex rather than the motor cortex. Although there is an overlap and cooperation with these cortex's, activation within the motor cortex has shown to be better triggered when performing a motor task, such as the exercises seen in virtual mirror therapy applications (Zhang et al., 2018). In contrast, the somatosensory cortex activates much more with tactile sensory stimuli, such as vibrations from texture and temperature differences (Purves, 2018). Research exploring the introduction of tactile sensation in a virtual mirror therapy protocol have shown promising results and Sano et al. (2016) has incorporated tactile sensation alongside audio cues into a common VMT protocol via the inclusion of vibrotactile actuators at the fingertips of the patient's intact fingers. Their application involves participants performing an active grasping task with their intact limb, which is reflected to where the phantom limb is experienced. When the participants grasp a virtual object in the application, tactile sensations are provided to the fingertips, alongside an audio cue, giving the illusion that the phantom limb is now touching the virtual objects. Sano et al. (2016) found that immediate pain was decreased to a greater degree when compared to the visual representation of the limb alone. This type of tactile stimulation realigns VMT with traditional mirror therapy in which the limb is visualised as well as manipulated in a proprioceptive and tactile fashion (Finn et al., 2017).

Although Sano et al. (2016)'s method has shown to be useful, there are many areas still to be explored. There is reason to believe a passive tactile sensation where a person experiences a touch that was not intentional or may not be expected, may invoke a greater or at least a different neural response in the somatosensory cortex, thus invoking alternative therapeutic properties (Ackerley et al., 2012; Simões-Franklin et al., 2011). In addition, Sano et al. (2016)'s protocol alongside tradition mirror therapy's use of contralateral mirroring of tactile sensation may not be feasible or appropriate for specific demographics such as bilateral amputees in which vibrotactile actuators cannot be utilised due to an intact limb not being present. Although there are other ways of virtually recreating the phantom limb's proprioception and visual characteristics using technology such as myoelectric sensors, that do not require an intact limb (Ortiz-Catalan et al., 2014). There is little research currently investigating how to deliver a tactile sensation to a portion of the limb without directly mirroring the sensation from one side of the body to the other as mirror therapy and virtual mirror therapy demonstrates. With this in consideration, it could be suggested here that a method of ipsilateral, distal relocation of passive tactile sensation could show to be beneficial for use in specific amputee demographics, which this paper aims to provide some insight.

1.3 Methods for Moving a Passive Tactile Sensation to a Distal Location

Although projecting a tactile sensation distally on a limb using visual capture techniques may seem straightforward given the observations found in mirror therapy and virtual mirror therapy, there is evidence that suggests the contrary. Previous experimentation has shown, simply presenting a light in a synchronous yet spatially distal location to a vibrotactile sensation, can disrupt tactile localisation via a visual capture response, but has failed to demonstrate a gross relocation of tactile sensations (Willis et al., 2019). Related studies using vibration arrays and visual light stimulus in augmented reality have shown similar results being able to relocate tactile perceptions around 40 mm. These results are interesting, but for phantom limb pain treatment, a more extensive relocation may be necessary (Niijima and Ogawa, 2014; Samad and Shams, 2018). In addition, there is also evidence that stimulation of the fingers, hand and forearm provided to one hand can also produce a neural response in section of the brain in responsible for processing touch of the opposite hand (Lamp et al., 2019). This suggests the visual capture response found in mirror therapy and virtual mirror therapy may be amplifying the results already present in normal perception allowing for an easier relocation of tactile sensation. These neural correlates have not yet been evidenced when referring touch to a different part of the limb. This may mean that distally relocating the tactile sensation may have some limiting capabilities compared to mirroring contralaterally.

Visual capture responses have been found to have long lasting effects that may provide insight for overcoming some of the limitations found in ipsilateral, distal, tactile relocation. These lasting effects are referred to as the ventriloquism aftereffect. The ventriloquism aftereffect details how a visual capture response can remain even though the visual stimulus that initially elicited it is no longer present Samad and Shams (2018). Unlike a visual capture response, the ventriloquist aftereffect has shown to be more flexible and mutable (Bosen et al., 2017). Bosen et al. (2017) discusses the how visual capture and the ventriloquism after effect may have separate neural mechanisms meaning they may not hold some of the neural limitations. Bosen et al. (2017) has demonstrated the ventriloquism aftereffect can be augmented and can accumulate after repeated exposure to a visuotactile pairing. Using a accumulated structured exposure to a visuotactile pairing to drive multiple ventriloquist aftereffects may be harnessed for a method of ipsilateral, distal relocation of passive tactile sensation for use in phantom limb pain treatment.

2 MATERIALS AND METHODS

The purpose of this study is to investigate whether a structured repeated exposure to a visual stimulus can relocate a passive tactile stimulus distally from the forearm to the fingers.

2.1 Hypothesis

1. Visual capture of a passive vibrotactile sensation can be distally relocated to larger degree with structured presentation of distally located visual stimulus rather than randomly presented visual stimulus.

2.2 Participants

A total of eight non-amputee participants were used in this study (five females, three males). Seven participants were right hand dominant, and 1 was Left hand dominant. Participants were recruited from the University of Portsmouth and were a mixture of staff and students. Age of the participants ranged from 19–40 years old. The exclusion criteria for this study were: Visual impairments which could not be corrected with visual aids such as glasses or contact lenses, visual field epilepsy, heightened tactile defensiveness, any known tactile discrimination deficits or recurrent/chronic pins and needles or numbness in the arms. None of the participants stated they felt any acute pain or were suffering from chronic pain. This study was reviewed by the University of Portsmouth ethics committee and given a favourable opinion following the University of Portsmouth guidelines. All participants gave written consent to take part in the study and for results to be published.

2.3 Variables

- Independent variable
- Visual stimulus presentation order (structured or random)
- Dependant Variable
- Section number in which the participants localised the tactile sensation

2.4 Groups

A between-groups study design was implemented. Participants were randomly allocated to one of two groups; a perceptually random group or a structured presentation group. These groups corresponded to the order that the participants viewed the visual light stimulus. All participants, no matter the group, conducted an initial tactile localisation without the presence of a visual light stimulus. This provided an initial baseline measurement for where participants localised the vibration actuators on there arm in regard to the virtual arm.

Participants in both the perceptually random group and the structured group experienced a vibrotactile stimulus in a consistent location on the arm and a temporally synchronous

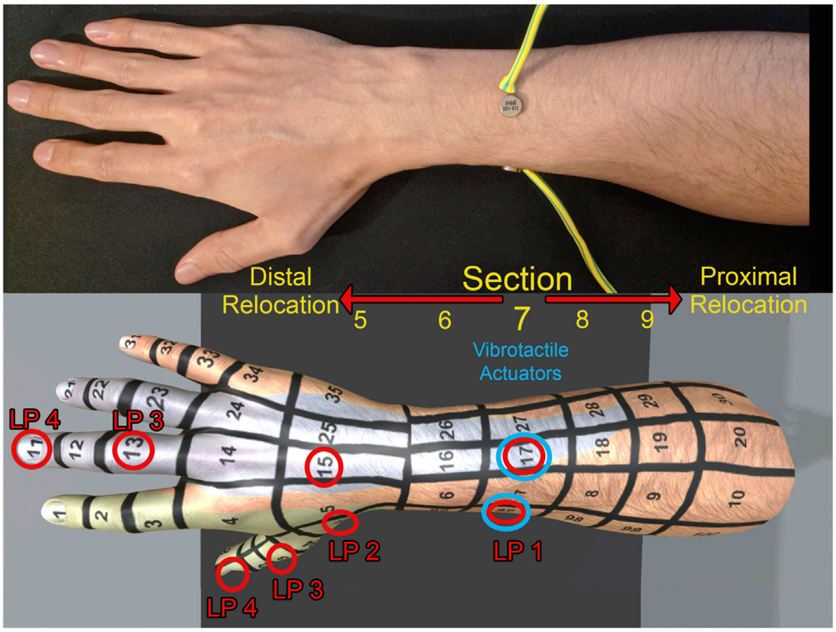

FIGURE 1 | Physical set-up of the vibration actuators on the arm **(A)** with the virtual fair skin male arm identifying light positions **(B)**. The physical vibration actuators were placed at section 17 and 97. LP = Light position. Positions of the lights are labeled in red and position of the physical vibration actuator labeled in blue. The arm models had a blue and green color map applied which signaled dermatomes and were used for verification of verbal response.

light stimulus. The visual light stimulus was presented either co-located or distally separated in three locations down the arm. The perceptually random group was presented the light in one of the four possible locations randomly each exposure. In contrast, the structured group experienced the lights, and vibrations initially co-located on the forearm and becoming more distally decoupled in discrete jumps in one location.

This study initially included an extra variable which was investigating whether dermatomes influenced the results of the visuo-tactile perception. It was hypothesised that there would be differences between whether the vibration motor was placed on a site that had multiple overlapping dermatomes or a single dermatome. This warranted the placement of two vibration actuators instead of just one. Participants therefore experienced the same conditions depending on the group they were allocated on both the overlapping dermatome and the single dermatome (Lee et al., 2008). There was a break of 5 min between experiencing the overlapping dermatome vibration sequence and the single dermatome sequence to avoid any carry over effect. When data was examined this variable was found to be innocuous and displayed no significant differences between the sites. Data was compiled in the analysis and reassessed to increase power. This meant the amount of exposures in each location was doubled from 8 to 16 exposures. See findings section.

2.5 Physical Set Up

Participants had two vibration actuators attached to the dorsal side of their forearms (**Figure 1**). These vibration actuators were separated on the lateral/medial plane of the arm but were proximally/distally in line. Medical adhesive was used to attach the vibration actuators. Each vibrotactile sensation experienced by the participants lasted for 1 s (230 Hz and 1.2 g amplitude). Placement of the vibration actuators was determined by measuring the participants' arms and adjusting the scale of the virtual arms to match. Measurements from the participants fingertips to their wrist was taken and a measurement from their wrist to their forearm created a scale factor for which the virtual model could be matched. Placement of the vibration actuators on the forearm was determined using the wrist in flexion as a reference point and measurements taken from the scaled virtual arm.

Due to the risk of participants remembering the positions of the vibration motors when they were applied to the skin, the lead researcher gave false indications that there may have been more motors attached to the arm. These false indications took the form of pressing the skin in random places along the forearm and hand. Placing inactive motors on the skin was proposed, however, results in Willis et al. (2019) showed that 7 of 16 people said people could faintly feel the presence of the vibration motors on the skin even when they were not vibrating. As participants were aware of the vibration actuators, it was suspected there was a chance to observe an unintended funnelling effect (Barghout et al., 2009). The funnelling effect can alter tactile localisation when two (or more) different locations simultaneously with different amplitudes can elicit phantom sensations in the space between (Lee et al., 2015). Instead, false presses on the skin were utilised to mask the true location as the tactile sensation from the presses should fade before the experiments measurements.

The vibration actuators were connected via wires to a core electronics platform worn on the participants back. Efforts were made to keep the wires away from the participants' arms by reinforcing the wires to give sufficient rigidity to trail away from the arms, ensuring that the only contact point on the participants were the attached vibration actuators. The vibrations were delivered through an Arduino mini pro, which communicated with unity via a serial cable. Each time the space bar was pressed by the lead researcher, a signal was sent to the Arduino issuing a command to a vibration motor to turn on and off.

2.6 Virtual Environment

The application was created in Unity and assets created in 3ds Max 2015. An Oculus Rift CV1 was used to display the virtual environment for the participant. A LEAP motion device was used to track the participants' hands and mapped the movement to the arms in the virtual environment. Tracking of the arms was checked before, and during for any overt latency issues which may have inhibited embodiment. None were present and participants did not report any when asked after the experiment. Participants were able to choose the appearance of the limb (male or female) and they had a choice of three different skin colors (fair, tan, and dark). Attached to these arms were eight virtual lights positioned in four locations on the arm (**Figure 1**). As the dermatome variable was removed due to having no significant effects on the results; and an overall focus on the distal/proximal localisation of the tactile sensation, the labeling denoting the section of where the lights were located have been standardised to use only the units. The units of the section corresponds to the distal/proximal location on the arm.

1. Located in **section 7** co-located with the vibrotactile actuator on the forearm
2. Located in **section 5** two sections distal from the vibrotactile actuator on the hand
3. Located in **section 3** four sections distal from the vibrotactile actuator on the finger
4. Located in **section 1** six sections distal from the vibrotactile actuator on the fingertip

The lights were switched off by default and when active remained present for 1 s. The light was rendered from Unity's halo function with an overall luminosity spanning 1.5 cm in a spherical manner (decaying to zero from 1 cm). Participants had a choice of either male or female arms. Sections were arranged in a grid format and followed anatomical landmarks such as fingers, wrist and knuckles. The arms were divided into 100 sections in total. These sections were not equal in size; however, each section was big enough for the vibration actuators and lights to fit into and were large enough to accommodate receptive fields (Purves, 2018). The sections ranged from 1 to 100 and wrapped around the arm. Numbers we ordered in a line from 1 (distal) to 10 (proximal) continued laterally around the arm. The number located in the sections of the grid were used by the participant to localise where they felt the vibration. A colored overlay was placed on the hands and forearms that represented the c6 and c8 dermatomes (this justification was not disclosed to participants). This colored overlay was for validation to mitigate human error in reporting, that was present during a pilot study of the study. Vocal verification of section with a color associated was encouraged. There is little evidence to suggest this coloring would influence relocation of the vibrotactile sensation, and upon inspection, there did not seem to be any influence.

TABLE 1 | Mann-Whitney *U* test results comparing the tactile localisation between the random group and the structured group at the different light positions.

	U value	*p* value	Effect size (R value)
No light condition	2021.500	0.896	0.01
Light position 1	1680.500	0.019*	−0.21
Light position 2	1439.000	0.002*	−0.274
Light position 3	1551.500	0.014*	−0.217
Light position 4	1802.500	0.221	−0.108

2.7 Task

Conditions were triggered by the lead researcher. Once triggered, a combination of vibrations and/or lights were presented to the participant depending on the phase the participant was in. Each participant was exposed to the no light condition to provide a baseline tactile localisation. Participants then proceeded on their group's intervention, either perceptually random lights or structured lights. After each condition, participants were asked to verbally state the section number they felt the vibration. This verbal response comprised the dependant variable. They were also asked to give any other comments about the experience after each condition. The timing between each condition was up to the participants' speed in verbally stating the section and conveying experiential data. Due to the time delay between exposure and response, it is unlikely any apparent motion illusions were experienced (Ueda et al., 2008). Participants were asked to keep the entire virtual arm in view for the duration of the study. Participants had agency of moving their arms throughout the study but were encouraged not to make any sudden or large arm movements or rotations, this limited the amount the cables moved and kept the tracking stable. The lead researcher made visual observations to make sure this was the case.

Arm fatigue was alleviated by enforcing breaks after trials 20, 40, and 60. This break was issued in the middle of a sequence not to disrupt the flow of the experiment and to limit any decay experienced in the possible ventriloquism aftereffect. Discomfort and pain have previously been shown to disrupt tactile acuity (Moseley et al., 2008). In order to mitigate this risk, participants were asked to lower their arms to their sides for a minimum of 30 s during the breaks, in order to recover from any arm or neck fatigue.

3 ANALYSIS AND FINDINGS

The dependant variable was the section number on the virtual arm that participants localised the vibration in. As the

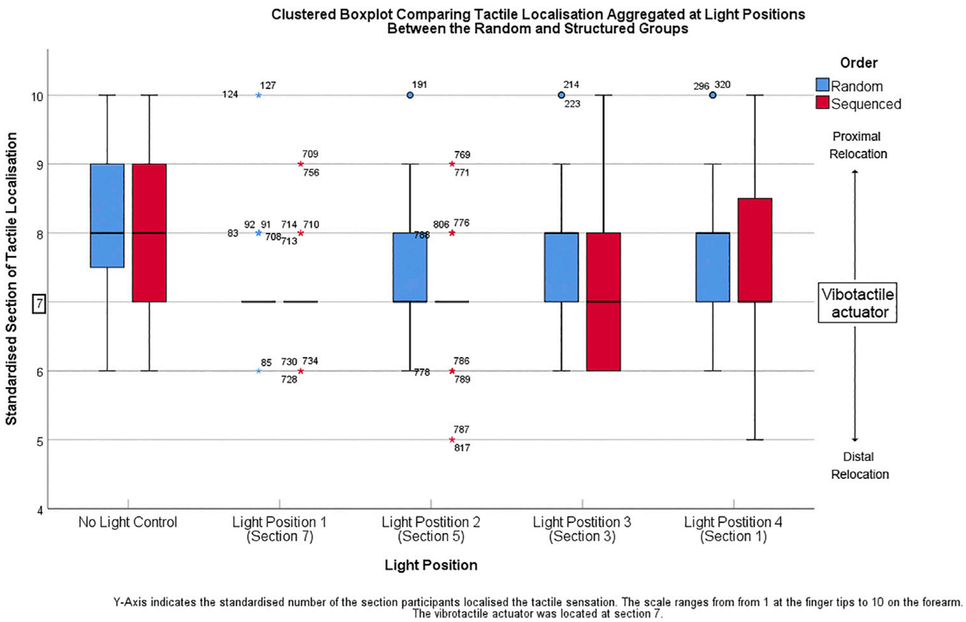

FIGURE 2 | Y-Axis shows the standardised number of the section participants localised the tactile sensation. The scale ranges from 1 at the finger tips to 10 on the forearm.

hypothesis is focused on distal relocation of the tactile localisation, responses have been standardised to only contain information regarding proximal and distal movement. This means lateral/medial relocation information has been removed for this analysis. For example, a response of section 17 will be interpreted as **section 7**, as the units of the section correspond to distal movement down the arm (1 = Distal, 10 = Proximal). This standardisation alongside the grid sections on the arm being varying sizes, meant all data collected could be treated ordinal in nature, thus making non-parametric tests most appropriate.

The study initially contained an extra variable investigating differences in tactile localisation between a vibration actuator placed in a position with overlapping dermatomes or a single dermatome, at the different light positions (see the **section 2.4**). Data was split isolating the Random group and the structured group so there was no influence of the presentation of lights. Tactile localisation during the no light condition and light positions was compared between the overlapping dermatome and single dermatome. A Levene's test showed data to be homogeneous across the light positions. A Mann-Whitney-U test was conducted and showed no significant difference of tactile localisation between the vibration sites at different light positions. No light (random), p = 0.765, No light (structured), p = 0.429, Light position 1 (Random), p = 0.08, Light position 2 (random), p = 0.14, Light position 3 (random), p = 0.053, Light position 4 (random), p = 0.081, Light position 1 (structured), p = 0.44, Light position 2 (structured), p250 = 0.05, Light position 3 (structured), p = 0.746, Light position 4 (structured), p = 0.672.

TABLE 2 | Pairwise comparisons investigating differences in tactile localisation between the light positions within the random and sequenced group. Each row tests the null hypothesis that Sample 1 and Sample 2 distributions are the same. Asymptotic significance's (2-sided tests) are displayed. The significance level is 0.05. Significance values have been adjusted by the Bonferroni correction for multiple tests. The table should be read vertically for individual groups.

	Random		Sequenced	
	Test Stat	Adj. Sig	Test Stat	Adj. Sig
No light control - Light position 1	34.0	0.000*	36.0	0.000*
No light control - Light position 2	4.57	0.325	21.5	0.000*
No light control - Light position 3	4.57	0.325	15.2	0.001*
No light control - Light position 4	5.68	0.172	11.3	0.008*
Light position 1 - Light position 2	8.69	0.032*	2.6	1.00
Light position 1 - Light position 3	10.8	0.010*	5.68	0.172
Light position 1 - Light position 4	10.8	0.010*	8.53	0.035*
Light position 2 - Light position 3	0.13	1.00	0.64	1.00
Light position 2 - Light position 4	0.13	1.00	1.86	1.00
Light position 3 - Light position 4	0.07	1.00	0.32	1.00

3.1 Differences in Tactile Localisation Between the Perceptually Random Group and Structured Group

Tactile localisation was compared between the random and structured groups at the light positions (no light, Light position 1, Light position 2, Light position 3, Light position 4) using a Mann-Whitney U tests (**Table 1**). 64 responses were recorded per group per location. When the light was not present on the arm, there were no significant differences between the random and structured groups ($p < 0.05$). There were significant differences in tactile localisation between the random and structured group when the light was present and located at position 1, 2, and 3 ($p < 0.02$). No significant differences were found when the light was located at the fingertips at position 4 ($p > 0.05$). Descriptive statistics were collected indicating the standardised section of tactile localisation at during the different conditions (**Figure 2**).

3.2 Differences in Tactile Localisation Between the Light Positions Within Groups

Pairwise comparison of tactile localisation between no light and the various light positions was compared within both the random and structured group using median tests (**Table 2**). The random group exhibited a difference in tactile localisation when the light was present at position 1, compared to the baseline localisation when the light was not present ($p = 0.000$). When the light was present at positions 2, 3, and 4 there were no significant differences compared to the baseline where no light was present ($p > 0.05$).

The structured group showed significant difference in tactile localisation when the light was located in all four positions (positions 1, 2, 3, and 4) compared to baseline condition where no light was present ($p < 0.008$). When the light was present in position 1 there was a significant difference in tactile localisation compared to light position 4 ($p = 0.035$). Tactile localisation showed no significant differences when the light was located at position 1 compared to light positions 2 and 3 ($p > 0.05$).

4 DISCUSSION

This study hypothesised that a structured presentation of lights positioned at increasingly distal locations of an arm would relocate a tactile sensation to a further degree than a random presentation of lights. Although significant differences have been found between the groups the results from this study do not support the stated hypothesis. Neither the random nor the structured group experienced a large displacement of the vibrotactile sensation as seen in virtual mirror therapy protocols. The groups demonstrated similar results regarding the overall distal displacement of the tactile perception on the arm. Both the random and structured groups initial perception of the vibrotactile stimulus; without an accompanying light stimulus, was proximally misplaced from the veridical vibration location (**section 7** to **section 8**). When a light accompanied the vibrotactile stimulation co-located at **section 7** participants calibrated their initially misplaced perception to where they now saw the light, signifying that a visual capture effect was observed. When the lights were positioned at more distal positions on the arm compared to the veridical vibrotactile site, the associative connection between the light and vibration creating the initial visual capture was not retained in a normal capacity. There were unexpected differences between how the random and structured group retained a visual capture situated at the veridical vibrotactile site. When the lights were presented distally from the vibrotactile site; meaning they were non co-located, the random group reverted to localising the tactile sensation at the initial, inaccurate location proximal to the veridical site. In contrast, when the structured group experienced the lights, distally non co-located at position 2 and 3 they retained the calibrated localisation at the veridical vibration site. There appeared to be a limit on this retention as when the light was located at position four on the fingers the visual capture response diminished and they started to localise the tactile sensation proximal once again from the veridical site. However, even as the visual capture diminished the distribution of response never reached the same extent as seen in their initial tactile localisation when a light was not present. It should be noted that the effect sizes for these results were small. In addition, the sample size for the demographic was also small, leading to potential issues with data diversity. As only eight people were used (four people in each group), caution needs to be taken when considering generalisability. Additional participants are required from a more diverse sample to externally validate.

Although careful measurements were taken to scale the virtual arms to match the participants own arms, there was an unexpected dissonance between where the vibrotactile actuators were physically located on their arm and where participants localised them on the virtual arm. This was evident in both the random and structured group when a visual stimulus did not accompany the vibration. They generally localised the vibrotactile sensation one section proximal from the veridical site. A possible reason for this observation may have been the appearance of the virtual limbs. Although the virtual arms were scaled to the correct size, there may have been perceptual inconsistencies with how the participants viewed and embodied them. The virtual arms lacked elbows, and this subsequently may have reduced the number of ways to infer where the vibration motors were. The only anatomical landmark provided to participants was the wrist. However, if a boundary for a proximal known anatomical landmark was provided such as an elbow, it is possible that tactile acuity may be increased. Another possible reason for proximal relocation may have been the false indications given to participants during the set up phase in an attempt to mask the true location of the vibration motors. However, false indications were only administered distal from the vibration sites meaning a proximal baseline is unlikely. Similar results have been reported demonstrating that tactile localisation can be perceived more proximal when a visual stimulus is occluded, suggesting there maybe psychophysical factors that need to be accounted for Badde et al. (2020). The inaccurate initial spatial localisation is not problematic to the overall results, as both groups are consistent, and the overall hypothesis is investigating whether a distal relocation is possible, which is a relative measurement.

Despite the discrepancies between the participants tactile mislocalisation and the veridical vibrotactile site; when a light was presented co-located with the vibrotactile actuator at position 1, tactile localisation to the veridical vibration site was significantly improved. This was evident in both the random and structured group. This relocation of tactile perception is likely attributed to a visual capture response as participants were displayed a bias toward the visual localisation over their initial tactile localisation. When the light was decoupled from the vibrotactile actuator in a spatially incongruent manner at position 2, 3, and 4, tactile localisation did not consistently follow the light. Instead, there was a significantly different response from the random group and the structured group. When the light was positioned at these distal locations, the random group regressed the tactile localisation to that experienced in the no-light condition. If visual capture only relied on visual dominance; where visual stimulus superseded tactile stimulation, it would have been expected that the tactile sensation moves to where the light was situated no matter the distance, when associated. However, this was not observed; Instead the random group generally switched back and forth between **section 7**, when the light was spatially co-located and **section 8** when the light was spatially non co located. This finding suggests visual dominance or a purely hierarchical organisation of sensory information is not the only component of sensory integration.

Conversely, the structured group retained their tactile localisation at the veridical vibrotactile site even when the lights were decoupled at more distal locations. Interestingly, when the light is present at position 4; instead of retaining the visual capture at the veridical vibrotactile site, localisation starts to diminish and regress proximally toward inaccurate initial tactile localisation when the light was not present. This suggests the retention of accurate tactile localisation at the vibrotactile site was not simply due to gradually establishing a better tactile localisation from cumulative exposure over time, but due to the visual stimulus retaining its effect over a greater distance until it reached a threshold distance. There are at least two possible explanations to this finding either a ventriloquist aftereffect was observed, or attention influenced the visual capture effects.

In the case of a ventriloquist aftereffect, there may have been a sufficient number of exposures at position 1; where the light was co-located at the veridical vibrotactile location, that an ongoing visual capture effect may have been observed even without the presence of the light for a finite duration (Frissen et al., 2012; Bosen et al., 2017). This finite duration may have been until the light reached light position 4. This explanation would provide evidence that visual capture and in extension the ventriloquist aftereffect is not mutable due to data from position 4 showing a proximal trajectory. Further research is needed to verify whether duration was the largest factor in the retention of accurate tactile localisation. Another explanation for the increased retention exhibited in the structured group may be due to attentional differences between the random presentation and the structured presentation. Increased attention to specific stimuli has shown to influence the degree and intensity of visual capture response (Odegaard et al., 2016; Badde et al., 2020). The structured group would have been able to expect and predict the movement of the light stimulus better than the random group, thus influencing the way participants divided their attention between the tactile sensation and the visual stimulus. Further research is necessary to conclude if attention may play a more important role than exposure in the movement of a tactile sensation.

Although a distal ipsilateral distal relocation of a tactile sensation was not observed to the extent that may be necessary for phantom limb pain treatment, the results corroborate and extend findings from Samad and Shams (2018) and Niijima and Ogawa (2014), where they observed around a 40 mm displacement. Due to standardising the section numbers in this study, a comparison to related findings cannot be made, regarding the gross amount of displacement in millimetres. However, on average the sections of the grid were longer than 40 mm in the proximal/distal plane. It is possible that the visual capture effects observed were larger than related studies. Further research is needed to quantify the distance relocated in a more granular fashion.

These results may be of use to other treatments such as graded motor imagery (GMI) in which tactile acuity is trained to improve. The structured groups results demonstrated that either a visual capture or ventriloquist aftereffect was established; however, even when the associated visual stimulus was moved, an accurate perception of where the vibrotactile sensation was located was retained. There is potential that the methods could be used to train tactile acuity without the concern that a visual capture response could potentially cause unintended results regarding tactile acuity.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. The open-source data is hosted on Figshare: https://doi.org/10.6084/m9.figshare.14527068.v1 (Willis, 2021).

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Portsmouth - Faculty of the Creative and Cultural Industries Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DW - First Authorship. BS - Senior Authorship, WP - Senior Authorship. DW, BS, and WP contributed to the idea of the project. DW and BS contributed to the methodology. DW created the virtual reality application and electronic peripherals, conducted the data collection, ran data analysis and wrote the majority of the paper. BS and WP contributed to the data analysis, structuring of the paper and reviewed and refined the paper.

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Pre-Exposure Cybersickness Assessment Within a Chronic Pain Population in Virtual Reality

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Virtual Reality (VR) is being increasingly explored as an adjunctive therapy for distraction from symptoms of chronic pain. However, using VR often causes cybersickness; a condition with symptoms similar to those of motion and simulator sickness. Cybersickness is commonly assessed using self-report questionnaires, such as the Simulator Sickness Questionnaire (SSQ), and is traditionally conducted post-exposure. It's usually safe to assume a zero baseline of cybersickness as participants are not anticipated to be exhibiting any sickness symptoms pre-exposure. However, amongst populations such as chronic pain patients, it's not unusual to experience symptoms of their condition or medication which could have a confounding influence on cybersickness symptom reporting. Therefore, in population groups where illness and medication use is common, assuming baseline is not necessarily desirable. This study aimed to investigate cybersickness baseline recordings amongst a chronic pain population, and highlights how deviations from an assumed baseline may incorrectly infer adverse effects arising from VR exposure. A repeated measures study design was used, in which twelve participants were assessed pre and post VR exposure via SSQ. Significant differences were found between actual and assumed pre-exposure baseline scores. Furthermore, we found significant differences between actual and assumed increases in cybersickness scores from baseline to post exposure. This study highlights that clinical sub-populations cannot be assumed to have a zero baseline SSQ score, and this should be taken into consideration when evaluating the usability of VR systems or interventions for participants from different demographics.

Keywords: virtual reality, cybersickness, chronic pain, self-report, baseline, pre-exposure

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INTRODUCTION

Virtual Reality (VR) is being used more often in medical and scientific research, for a variety of applications (Riva, 2005; Malloy and Milling, 2010; Valmaggia et al., 2016; Vaughan et al., 2016), and has been demonstrated as a powerful and flexible technology which is also affordable and relatively easy to use.

However, in spite of the rich potential of this technology for use in healthcare, it is common for persons to prematurely exit a VR experience because of symptoms associated with cybersickness (McCauley and Sharkey, 1992; Garrett et al., 2017). Cybersickness is defined as onset of nausea, oculomotor, and/or disorientation while experiencing virtual environments (Rebenitsch and Owen, 2016). This can cause problems for VR users as discomfort caused as a result of cybersickness prevents interaction longevity (Davis et al., 2015).

Symptoms of cybersickness can include nausea, headaches, dizziness, eyestrain, sweating, and disorientation (LaViola, 2000). It has been reported that as many as 80% of participants experience an increase in symptoms within 10 min of being exposed to VR (Kim et al., 2005; Cobb et al., 1999), and although these studies pre-date consumer VR, recent research indicates that this issue is still prevalent (Yildirim, 2020).

Although it's clear that side effects from VR exposure exist, there is a lack of consistency in the literature regarding the precise definitions. Rebenitsch and Owen (2016) describe the symptoms of cybersickness produced in users of VR systems to "mimic motion sickness, but due to the absence of actual physical motion this affliction is considered a distinct condition referred to as cybersickness." Cybersickness has been referred to also as visually induced motion sickness (VIMS), virtual simulation sickness, virtual reality-induced symptoms and effects, amongst other terms, as well as commonly being misinterpreted as simulator sickness. Cybersickness is distinctly separate from simulator sickness by the characteristics of its symptom profile, and the apparent disparity in symptom intensity (Stanney et al., 1997).

There is some discussion in the literature regarding other terms for these effects, for example '*virtual reality-induced symptoms and effect*' (Cobb et al., 1999). However, for clarity, in this paper we will refer to the side effects of VR exposure as '*Cybersickness*,' as this is the term most commonly used in the literature under discussion. We acknowledge that future work in this field should be considering updated terminology in order to describe the symptoms.

The safety of a device or intervention should be paramount when determining whether it is suitable for its intended audience, especially when developing novel applications for the purpose of medical interventions, rehabilitation, or training.

For clinical VR research, it is common to evaluate whether the VR system causes cybersickness symptoms, and thus determining whether it is safe to implement compared to an alternative intervention. For example, VR is being used more commonly within military environments where retention of information and task performance is vital, and thus information inhibition caused by cybersickness symptoms is an important consideration (Stanney et al., 2020).

Aside from the safety considerations, cybersickness may have implications for other factors in immersive systems. It has been suggested that individuals who report greater sickness symptoms in VR could be expected to report less presence (Witmer and Singer, 1998; Weech et al., 2019), which may have unwanted effects on desired outcomes. For example, when VR is used for the purposes of pain distraction, presence is considered a major contributor toward pain alleviation being achieved (Hoffman et al., 2004; Wiederhold et al., 2014). It is therefore important to test for factors, such as, cybersickness, which could potentially affect treatment outcomes. It is recommended that applications should be tested for cybersickness, and evaluated at the feasibility stage (Lubetzky et al., 2018; Davis, Nesbitt, and Nalivaiko, 2015).

Cybersickness is traditionally measured using self-report questionnaires, with the most commonly used being the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). The SSQ was developed for use with simulators, and was adapted from Kennedy's work in developing the Pensacola Motion Sickness Questionnaire (Kennedy et al., 1965), however it has been adopted widely for use with Virtual Environments (VE), as their symptom profiles and sickness characteristics are similar (Stanney et al., 1997).

A number of other self-assessment questionnaires have been devised for monitoring cybersickness, such as the Virtual Reality Symptom Questionnaire (Ames et al., 2005), and the Virtual Reality Sickness Questionnaire (Kim et al., 2018)–an adaption of Kennedy's SSQ, have been used sporadically. A common criticism of these self-report questionnaires has been that they take too long to administer, therefore shorter single question measures have been used also (Nalivaiko et al., 2015; Keshavarz and Hecht, 2011). Aside from questionnaires, assessment of cybersickness by means of postural instability has been used more recently (Risi and Palmisano, 2019), as postural stability has been suggested to be a cause of the experience of cybersickness (as it has similarly been hypothesised to be a contributing factor in the cause of simulator sickness) (Stoffregen et al., 2000), although conflicting opinions exist (Dennison and D'Zmura, 2017).

There is a surprisingly limited discussion in the literature regarding what is considered a 'normal' score for cybersickness amongst healthy or non-healthy populations. In relation to the SSQ, amongst healthy participants, it is not usually necessary to perform sickness questionnaires pre-exposure as a baseline SSQ score could reasonably be assumed to be 0 (indicating no symptoms). However, participants from clinical populations may exhibit symptoms similar to cybersickness pre-exposure, and thus for these populations, the assumed zero baseline may be incorrect. For example, Bouchard et al. (2009) reported non-zero pre-exposure scores amongst participants with selected anxieties.

Kennedy et al. (1993) did suggest that pre-exposure screening of participants should be administered, but went onto recommend that individuals in a state other than their usual fitness (who score a non-zero pre-exposure score) should be eliminated from further participation, and thus only post-exposure assessment should be scored. However, if we only test on healthy participants, we can never test with clinical populations (such as people with chronic pain). Likewise, if we removed the participants who answered as anything other than 'well,' we would be removing the target population we are trying to study, which in turn would not facilitate clinical work being conducted. Amongst clinical populations such as chronic pain patients, it would certainly be counter-productive to eliminate individuals in this capacity as it has been suggested that confounders between cybersickness and medication exists (McCauley and Sharkey, 1992). Furthermore, understanding the pre-exposure state is important, as any pre-exposure symptoms could influence the interpretation of post-exposure scoring (Kennedy et al., 1993). Thus we suggest that it would be more informative to assess cybersickness pre-exposure, and observe changes which may occur between pre and post-exposure assessment. Without pre-exposure assessment, incorrect conclusions about the effect of a VR intervention could be formulated.

In lieu of pre-exposure assessment via SSQ, instruments such as, the Motion Sickness Susceptibility Questionnaire (Golding, 1998) may be administered to assess susceptibility to symptoms. However, susceptibility questioning alone does not reflect the current state of patients, but rather previous experiences within motion sickness-inducing situations, which is not indicative of determining the effect of a VR intervention.

To date, much of the pain research concerned with pain populations does not include any type of sickness assessment as part of their study protocols–including post-exposure sickness questionnaires. However, there are a few which do measure or discuss pre-exposure baseline or pre-exposure symptoms (e.g., Sarig Bahat et al., 2015; Wiederhold et al., 2014; Bouchard et al., 2009). Kennedy et al. (1993) suggested that sickness susceptibility questionnaires could be used as an alternative to pre-exposure baseline testing. However, in the majority of pain research in VR, neither this nor other pre-exposure baseline symptom testing measure is used, nor is the potential need for them discussed. Furthermore, susceptibility questionnaires do not elicit data regarding current symptoms, and therefore do not address the issue of a non-zero baseline score.

As the SSQ is currently the most widely use measure for cybersickness, we use this measure pre and post-exposure in order to facilitate comparisons with other work. The most common approach for assessing results of the SSQ is Kennedy et al.'s. weighted scoring (1993), although this has been criticised for scores being inflated by counting items multiple times in the total score calculation (Bouchard et al., 2007). Alternative scoring methodologies have been proposed, such as Bouchard et al. (2007) revised factor structure which proposes assessment with raw scores, rather than Kennedy's weighted score calculation.

We suggest that it is important to understand whether some clinical populations may present pre-existing symptoms similar to symptoms of cybersickness (**H1**). Furthermore, it has been observed previously that cybersickness symptom scores may decrease rather than increase as the result of a VR intervention, (e.g., Bouchard et al. , 2009). A decrease in cybersickness-like symptoms in such a population may still give a post-exposure score greater than the zero baseline (**H2**). It could be hypothesised that a direct comparison of post-exposure SSQ scores between healthy and pain populations cybersickness scorings post-VR intervention may indicate that an intervention has made the pain population sicker than the healthy population. However, if pre-exposure (baseline) cybersickness scores were taken into account, then it may be that the any difference is due to a baseline difference, and not caused by the intervention itself (**H3**).

H1—The pain population will have significantly higher pre-exposure SSQ scores than the normal population assumed baseline.

H2—The pain population will have significantly higher post-exposure SSQ scores than the normal population assumed baseline of zero.

H3—The difference in SSQ scores from pre-exposure to post-exposure will be significantly less than the difference between the assumed baseline score and the post-exposure score.

TABLE 1 | Participant demographical information.

	Male	Female	
Gender (*N*)	5	7	
	Nociceptive	Neuropathic	Unknown
Cause of pain (*N*)	8	3	1

METHODS

The participants for this study were drawn from a population of Chronic Pain patients, as this group has been identified as one which may present pre-existing symptoms (McCauley and Sharkey, 1992). In order to reduce the burden on the patient population, this SSQ study was conducted alongside a study observing the effect of VR on experimentally induced pain in Chronic Pain patients, which describes the study methods and procedure summarised here in more depth.

Participants

Twelve participants aged 39–70 ($M = 56 \pm 9.36$) (**Table 1**) were recruited from a United Kingdom pain support group and networks. All participants had been experiencing chronic pain (defined as a period lasting 3 months or greater). Participants also completed pre-study screening questionnaires to exclude any factors which would prevent them from participating in a VR study. Factors for exclusion included health issues which could prevent someone from using a visual display for an extended period of time.

Design

A within-subjects, repeated measures study design was used. Pre-exposure SSQ was recorded before participants were randomised to receive either an active or passive VR distraction in a counterbalanced order. The passive intervention was part of the parallel study and is not considered further in this paper. In line with previous literature relating to SSQ scores, in this study we are only considering post-active SSQ results referred to hereon as post-exposure, unless explicitly stated otherwise.

Hardware and Software

The software interventions used were 1) Bananaland. An active intervention and a proprietary VR experience, in which the user traverses through a jungle environment with ambient music accompanying the visuals. 2) A passive intervention which consisted of grey lines on the screen. In this condition users could look around however no dynamic visual feedback was present. This was designed to be neutral and non-engaging.

Both interventions were presented using an Oculus Rift CV1 Head Mounted Display (HMD).

TABLE 2 | Pre and post exposure SSQ scores for pain participants.

Participant	Pre-exposure baseline (weighted)	SSQ score Pre-exposure baseline (non-weighted)	Post-exposure (weighted)	Post-exposure (non-weighted)
1	7.48	2	18.7	5
2	7.48	2	14.96	4
3	0	0	0	0
4	44.88	12	33.66	9
5	0	0	3.74	1
6	11.22	3	11.22	3
7	7.48	2	63.58	17
8	3.74	1	3.74	1
9	14.96	4	22.44	6
10	7.48	2	14.96	4
11	3.74	1	14.96	4
12	14.96	4	18.7	5
Mean	10.29	2.75	18.39	4.92
SD	11.44	3.19	16.19	4.52

Procedure

Participants were asked to sign a consent, and were asked to confirm that no changes had occurred since registering that might be applicable to the studies medical exclusion criteria.

Before any VR intervention, participants completed a pre-exposure (baseline) SSQ. As per the protocol for the accompanying study, participants were induced with experimental pain by means of a pressure cuff inflated to and sustained at 200 mmHg, and applied to their non-dominant arm. This procedure was conducted in accordance with the Submaximal Tourniquet Effort Test (SMET) (Moore et al., 1979).

Participants were then exposed to the VR intervention for a maximum of 5 min, or until the participant asked to exit, which they were able to do at any point. After the completion of each VR session, participants completed a post-exposure SSQ. After each session, the participant was given time to rest before continuing.

The study was approved by the University of Portsmouth institutional review board.

Data Analysis

A Shapiro–Wilk test of normality indicated that pre-test sickness scoring was not normally distributed ($p = 0.001$). A Shapiro-wilk test of normality indicated that the post-test sickness scoring was not normally distributed ($p = 0.014$).

As this work is concerned with being comparable in the relevant literature, we will be calculating our results using Kennedy's traditional approach, although will also apply Bouchard et al. (2007) revised factor structure and scoring where applicable.

A Wilcoxon signed-rank test was performed to assess whether our study sample had a significantly higher pre-exposure SSQ scores than the normal population assumed baseline. A Wilcoxon signed-rank test was performed to assess whether our study sample had a significantly higher post-exposure SSQ scores than the normal population assumed baseline. A Mann-Whitney *U* test was performed to assess whether the difference in SSQ scores from pre and post-exposure of our study sample will be significantly less than the difference the assumed baseline score and the post-exposure score of our study sample.

RESULTS

Descriptive statistics for the pre-exposure and both post-exposure SSQ scores are shown in **Table 2**, and **Figures 1** and **2**.

All scores referred to as weighted have been calculated using Kennedy et al. 1993) method. References to non-weighted scores are applying Bouchard et al. (2007) scoring approach.

(1) Pre-exposure SSQ scores compared to the assumed baseline (zero) of healthy participants.

A Wilcoxon signed-rank test indicated that the pre-exposure scores were significantly greater than the assumed baseline (zero) ($z = 55$, $p = 0.005$).

(2) Post-exposure SSQ scores compared to the assumed baseline (zero) of healthy participants.

A Wilcoxon signed-rank test indicated that a significantly higher post-exposure score than the assumed baseline (zero) was reported ($z = 66$, $p = 0.003$).

The mean post-exposure score obtained from our participants was 18.39, with high variability as the SD for the post-exposure was 16.19 (**Table 1**).

(3) Comparing post-exposure differences between actual and assumed baseline SSQ scores

A Mann–Whitney *U* test indicated that the difference between the pre and post-exposure SSQ scores was significantly less than the difference between the assumed baseline and post-exposure SSQ score ($z = -2.297$, $p = 0.020$) (**Figure 3**).

A Mann-Whitney *U* test performed using Bouchard et al. (2007) non-weighting scoring approach indicated that the difference between the pre and post-exposure SSQ scores was significantly less than the difference between the assumed baseline and post-exposure SSQ score ($z = -2.297$, $p = 0.020$).

Individual items of the SSQ are categorised into subscales which are distinct symptom clusters (Kennedy et al., 1993). We

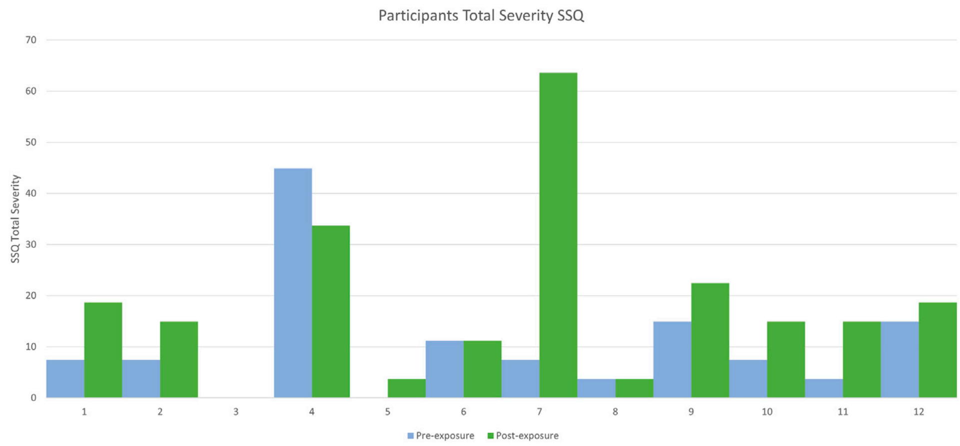

FIGURE 1 | Weighted total severity SSQ scores pre-exposure and post-exposure of VR interventions.

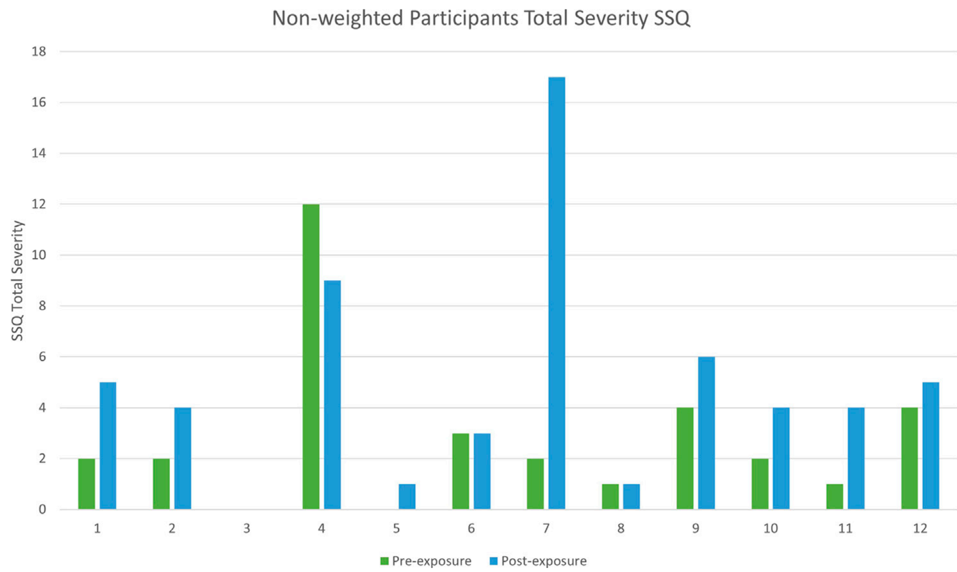

FIGURE 2 | Non-weighted total severity SSQ scores pre-exposure and post-exposure.

therefore also scored each symptom cluster independently (**Table 3**).

There was an approximately 10 point increase in mean weighted SSQ scores in each of the sub categories, with the greatest variability being observed in the disorientation sub category. Whilst increases in mean SSQ scores were noted in all three categories, the symptom profile remained the same pre and post exposure.

DISCUSSION

In this study, we theorised that using post-exposure SSQ scores in VR studies may lead to misinterpretation of results in some clinical populations such as those with chronic pain. To investigate this, we formulated three hypotheses regarding how pain participants cybersickness scores would compare to an assumed baseline scoring of the healthy population, and whether the pre-exposure state of pain participants differs from healthy participants assumed baseline.

We first hypothesised that a chronic pain population will have a higher than zero baseline SSQ score than the normal population. Our results indicate that a significant difference between the assumed (zero) baseline, and the measured pre-exposure SSQ scores exists, supporting the hypothesis. Much of the existing literature relies on post-exposure SSQ scores

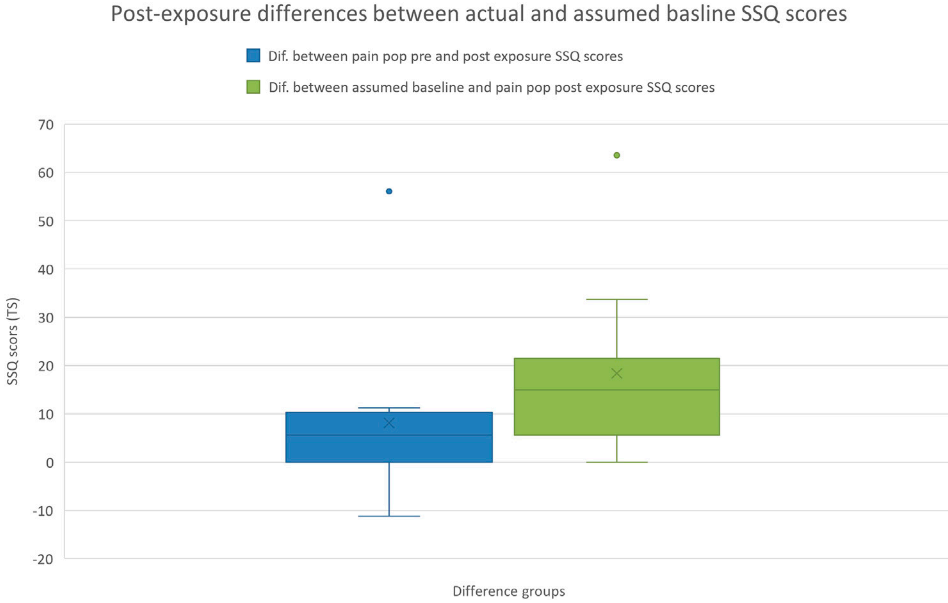

FIGURE 3 | Post exposure differences between actual and assumed baseline SSQ scores.

TABLE 3 | SSQ symptom sub category scores.

	Mean	SD	Min	Max
Oculomotor				
Pre-exposure (weighted)	18.318	19.439	0	75.8
Pre-exposure (non-weighted)	1.417	2.431	0	9
Post-exposure (weighted)	25.267	18.908	0	68.22
Post-exposure (non-weighted)	2.167	2.375	0	8
Nausea				
Pre-exposure (weighted)	15.105	13.184	0	47.7
Pre-exposure (non-weighted)	1.33	1.027	0	3
Post-exposure (weighted)	23.055	11.327	0	38.16
Post-exposure (non-weighted)	2.75	2.203	0	9
Disorientation				
Pre-exposure	2.32	7.695	0	27.84
Post-exposure	12.76	34.781	0	125.28

only, and few studies to date are concerned with determining the pre-exposure condition (Sarig Bahat et al., 2015; Wiederhold et al., 2014). Whilst this may be of limited importance if we are only interested in absolute SSQ score post-exposure, it becomes highly relevant when comparing the effect of VR exposure between different populations. We cannot assume that all population sub-groups will be starting studies at the same baseline, and this could affect the interpretation of post-exposure scores.

Secondly, we hypothesised that a chronic pain population will have greater post-exposure SSQ scores than the assumed (zero) baseline. Our results indicate that a significant difference does indeed exist. We expect with a VR intervention that participants will report some, potentially significant, cybersickness post-exposure, as it is unlikely to be zero. However, when assuming the comparison against a zero baseline, the result is not necessarily indicative of the VR interventions causation. This highlights potential disparities when using assumed baselines amongst groups such as chronic pain participants (who likely enter studies with elevated baselines). Furthermore, one participants cybersickness symptoms actually decreased between pre and post-VR intervention (**Figure 1**), supporting similar observations made by Bouchard et al. (2009). This result also supports our first hypothesis that assuming baselines can affect the interpretation of post-exposure scoring.

Thirdly, we hypothesised that the difference between SSQ scores of the pre and post-exposure would be significantly less than the difference between the assumed baseline and the post-exposure SSQ scores. Our results demonstrated that the difference in SSQ scores measured pre to post was significantly less than the difference in SSQ scores measured between the assumed baseline and post-exposure (**Figure 3**). If we aim to determine whether an intervention has caused cybersickness, by just collecting and observing post-exposure scores we may conclude that it does (when compared to zero). However, if we are able to look at our populations incoming SSQ score, it may be that the intervention has little or no negative effect by comparison. Furthermore, this result demonstrates how if these results were analysed without a known baseline and just the assumed (zero) baseline, that a false positive effect of the intervention on SSQ would have been reported. In the absence of pre-exposure or susceptibility testing (Golding, 1998), just post-exposure SSQ scoring could indicate that the pain population would become sicker than the healthy population, and could ultimately conclude that an application is unsuitable for the non-healthy population.

TABLE 4 | Severity of symptoms in spectral profiles.

High to low ↓	Simulator sickness	Cybersickness
	Oculomotor	Disorientation
	Nausea	Nausea
	Disorientation	Oculomotor

However, if pre-exposure testing is conducted, it's possible that the rate of change in both populations is comparable, and therefore the application is equally suitable for both.

This is of particular importance for pain populations, as the literature highlights how cybersickness may be negatively correlated with presence (Witmer and Singer, 1998; Weech et al.,, 2019), which is considered a key reason for VR's efficacy of providing pain alleviation via distraction, as it's suggested to be positively correlated with presence (Hoffman et al., 2004; Wiederhold et al., 2014).

While difference scoring alone is not generally considered a valid measure due to potentially poor reliability (Cronbach and Furby, 1970; Young et al., 2006), our result nevertheless demonstrates the importance of understanding pre-exposure symptoms of a clinical population when examining the effect of cybersickness When considering whether the symptoms of cybersickness become exacerbated in a VR application, basing our assumptions on purely on the post-exposure SSQ scores would be misleading.

The SSQ categorises symptoms into three distinct clusters which are Oculomotor, Nausea, and Disorientation (Kennedy et al., 1993). Spectral profiles of sickness exist to define cybersickness from the often misinterpreted simulator sickness (Stanney et al., 1997), with simulator sickness following the symptom profile of Oculomotor, Nausea, and Disorientation; in order of perceived symptom severity. Cybersickness however is suggested to follows the symptom profile of Disorientation, Nausea, and Oculomotor (Stanney et al., 1997) (**Table 4**). Although examining the differences between the SSQ subcategories was not a primary aim of this study, and is thus purely observational, we noted that the reported SSQ symptoms did not follow the symptom profiles which traditionally defines cybersickness uniquely (**Figure 4**). We observed that the symptom profile of participants was similar to that of simulator sickness (**Table 4**), rather than that of cybersickness. The literature has previously highlighted discrepancies in cybersickness/simulator sickness spectral profile definitions, suggesting that users affected with cybersickness have followed symptom profiles different to that reported by Stanney et al. (1997) and Gavgani et al. (2018). Although this cannot be generalised for the population as this is a small sample, this effect should be looked into further with a larger sample.

This could be because rather than following symptom profiles devised to categorise cybersickness, pain participants are exhibiting symptoms associated with chronic pain symptom profiles. For example, at pre and post-exposure our participants scored highest in Oculomotor and Nausea (**Table 3**). Oculomotor elements include fatigue, headache, eye strain, and difficulty focusing, similar to some somatic symptoms associated with chronic pain which includes fatigue, unrefreshing sleep, and dyscognition (difficulty concentrating and thinking) (Wolfe et al., 2010; Crofford, 2015). Nausea elements include feeling nauseous and dizziness, which are also common side effects of opioid based medication, such as Hydrocodone and Fentanyl, commonly prescribed for the treatment of chronic pain (Benyamin et al., 2008). However, when observing the rate of increase between pre and post-exposure, the rate of which symptoms have increased is comparable to the traditionally proposed symptom severity of cybersickness (**Figure 4**). This would indicate that participants entered with symptoms of their illness, which is comparable to Simulator Sickness and pain symptom profiles, however their increase is representative of cybersickness. Future work could further investigate the symptom profiles of clinical sub-populations

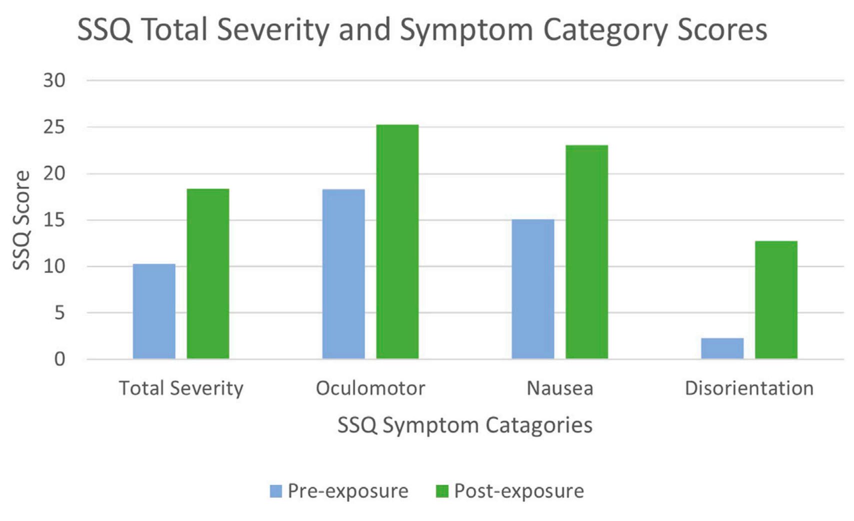

FIGURE 4 | SSQ total severity and symptom category scores.

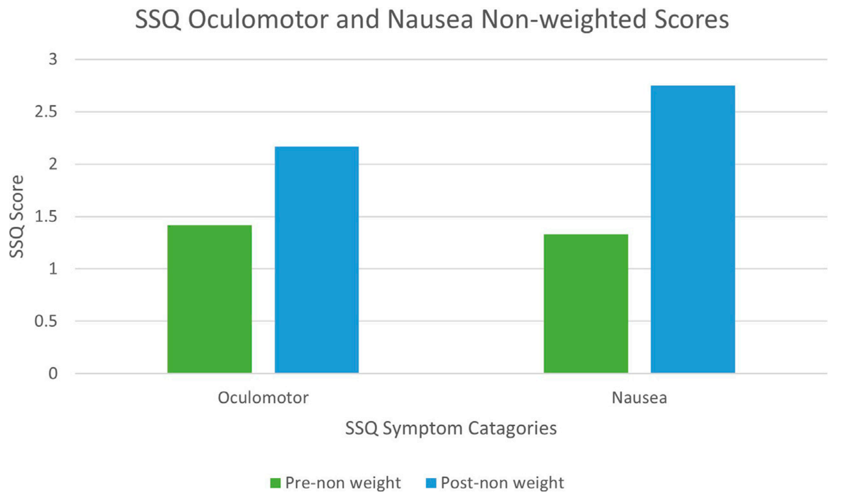

FIGURE 5 | SSQ oculomotor and nausea non-weighted scores.

pre and post-exposure, which may give some indication as to whether post-exposure SSQ scores are more attributable to the VR intervention or the pre-existing clinical condition.

It's also possible that the experimentally induced painful stimuli experienced during the parallel study may have caused an increase in the pain-related symptoms, which overlap with the SSQ symptom list. Further studies using a VR exposure for this group without the experimentally induced pain would control for this possible confounding factor. It has be argued that pre-exposure may influence post-exposure results (Kim et al., 2005; Young et al., 2006). In these previous studies they show a significant increase when given pre-exposure questionnaires, an effect which we did not observe. Future work could explore pre-exposure bias when administering the SSQ further.

Two participants reported a pre-exposure SSQ score comparable to the normal populations assumed baseline (zero), with the mean pre-exposure SSQ for the pain participants being 10.29. A high SD of 11.44 was reported, indicating that reported pre-exposure SSQ scores were highly variable (**Table 1**), which is representative of pain populations variability and individuality of symptom exhibition (Allen et al., 2009; Bartley et al., 2018). Of the 12 participants, 9 had a post-exposure score greater than 10, only 2 of these showed a substantial increase on pre-exposure scores, and all 9 had a non-zero pre-exposure score. However, 1 participant did show a decrease is symptoms as oppose to an increase (**Figure 1**).

Using Bouchard et al. (2007) scoring approach, a comparable Mann-Witney *U* test was performed which returned the same confidence interval as we observed when using Kennedy's scoring. Similar differences were also observed when scoring the Nausea and Oculomotor sub-scales respectively (**Figure 5**). Therefore, although in other contexts Bouchard's scoring may give rise to different conclusions, for the purposes of this study both Bouchard's and Kennedy's approaches lead to the same conclusions.

We would like to acknowledge also that although the focus of this work was to highlight that certain populations may not be as adversely affected as SSQ scores might indicate, it is possible that starting with a non-zero pre-score might mean that when participants do become sick because of VR, the rate which their sickness increases may be greater than someone who entered the study with a zero baseline score. Alternatively, entering with a non-zero baseline score could also provide greater resilience to symptoms when interacting within VR. Kruk,(1992) suggests that medication increases the susceptibility to simulator sickness. Although little work exists as to whether this same interaction exists for cybersickness, McCauley and Sharkey 1992) suggest that problems with cybersickness symptoms may be exacerbated by medication. Further work could be warranted to explore these points.

This study has highlighted that some sub-populations cannot be assumed to have a zero baseline. 10 out of 12 participants enrolled in this study entered with a non-zero baseline, confirming that assumed baselines should not be an indicator for informed research concerned with measuring cybersickness amongst non-healthy populations. and that considerations should be taken when evaluating the usability of VR systems or interventions for participants from different demographics.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Portsmouth CCi. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

The study was designed by PB and WP. The data acquisition was conducted by PB. Formal analysis was conducted by PB with statistical advice provided by WP. Supervision for this study was completed by WP. The author who took lead on writing the manuscript was PB, and main feedback and edits were provided by WP. All authors contributed feedback to the final version of the manuscript.

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ORIGINAL RESEARCH
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Effects of Sensory Feedback and Collider Size on Reach-to-Grasp Coordination in Haptic-Free Virtual Reality

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Technological advancements and increased access have prompted the adoption of head-mounted display based virtual reality (VR) for neuroscientific research, manual skill training, and neurological rehabilitation. Applications that focus on manual interaction within the virtual environment (VE), especially haptic-free VR, critically depend on virtual hand-object collision detection. Knowledge about how multisensory integration related to hand-object collisions affects perception-action dynamics and reach-to-grasp coordination is needed to enhance the immersiveness of interactive VR. Here, we explored whether and to what extent sensory substitution for haptic feedback of hand-object collision (visual, audio, or audiovisual) and collider size (size of spherical pointers representing the fingertips) influences reach-to-grasp kinematics. In Study 1, visual, auditory, or combined feedback were compared as sensory substitutes to indicate the successful grasp of a virtual object during reach-to-grasp actions. In Study 2, participants reached to grasp virtual objects using spherical colliders of different diameters to test if virtual collider size impacts reach-to-grasp. Our data indicate that collider size but not sensory feedback modality significantly affected the kinematics of grasping. Larger colliders led to a smaller size-normalized peak aperture. We discuss this finding in the context of a possible influence of spherical collider size on the perception of the virtual object's size and hence effects on motor planning of reach-to-grasp. Critically, reach-to-grasp spatiotemporal coordination patterns were robust to manipulations of sensory feedback modality and spherical collider size, suggesting that the nervous system adjusted the reach (transport) component commensurately to the changes in the grasp (aperture) component. These results have important implications for research, commercial, industrial, and clinical applications of VR.

Keywords: visual feedback, auditory feedback, haptic feedback, collision detection, prehension, virtual environment, virtual reality

1 INTRODUCTION

Natural hand-object interactions are critical for a fully immersive virtual reality (VR) experience. In the real world, reach-to-grasp coordination is facilitated by congruent visual and proprioceptive feedback of limb position and orientation and haptic feedback of object properties (Bingham et al., 2007; Coats et al., 2008; Bingham and Mon-Williams, 2013; Bozzacchi et al., 2014; Whitwell et al., 2015; Bozzacchi et al., 2016; Hosang et al., 2016; Volcic and Domini, 2016; Bozzacchi et al., 2018). In virtual environments (VE), visual feedback of the avatar hand may be incongruent with proprioceptive feedback from the biological hand. This discrepancy can arise from technological limitations (e.g., latency, rendering speed, and tracking accuracy) related to how the scene is calibrated (Stanney, 2002) or how the VR task is manipulated (Groen and Werkhoven, 1998; Prachyabrued and Borst, 2013). Moreover, the virtual representation of the limb may be distorted in appearance (Argelaguet et al., 2016; Liu et al., 2019) in a similar manner to the use of a cursor to represent hand position in traditional computer displays. For example, visualization of the index finger and thumb as simple spherical colliders to allow pincer grasping of objects in VE is often employed (Furmanek et al., 2019; van Polanen et al., 2019; Mangalam et al., 2021). The colliders' size is often arbitrarily chosen by researchers but can have profound effects on behavior, especially for dexterous and accuracy-demanding tasks. Finally, when not combined with haptic devices, haptic information about whether and how a given object has been grasped is absent, creating additional uncertainty. The lack of haptic feedback about object properties may be supplemented with terminal visual feedback (sensory substitution) in the form of the object changing its color, or as auditory feedback in the form of a sound, to signal that the virtual object has been contacted or grasped and to minimize hand-object interpenetration (Zahariev and MacKenzie, 2003; Zahariev and MacKenzie, 2007; Castiello et al., 2010; Sedda et al., 2011; Prachyabrued and Borst, 2012; Prachyabrued and Borst, 2014; Canales and Jörg, 2020).

One of the most common and well-studied forms of hand-object interactions is reaching and grasping an object. Reach-to-grasp movements involve a reach component describing the transport of the hand toward the object and a grasp component describing the preshaping of the fingers to the object. Traditionally, the end of a "reach-to-grasp" movement is defined by contact with the object. The reach component is quantified through analysis of hand transport kinematics (e.g., trajectory and velocity of the wrist motion), and the grasp component is quantified through analysis of aperture kinematics (e.g., interdigit distance in time) (Jeannerod, 1981; Jeannerod, 1984). Planning and execution of successful reach-to-grasp movements require both spatial and temporal coordination between the reach and grasp components (Rand et al., 2008; Furmanek et al., 2019; Mangalam et al., 2021). Whether the transport and aperture components represent information flow in independent neural channels remains an open and interesting question (Culham et al., 2006; Vesia and Crawford, 2012; Schettino et al., 2017); however, several kinematic features of coordination between the two components have been well described (Haggard and Wing, 1991; Paulignan et al., 1991a; Paulignan et al., 1991b; Gentilucci et al., 1992; Haggard and Wing, 1995; Dubrowski et al., 2002). For instance, peak transport velocity tends to occur at 30% of the total time to complete the movement (Jeannerod, 1984), and peak aperture (maximal hand opening) occurs at 60–70% of total movement time (Castiello, 2005). Furthermore, there is substantial evidence to support that the grasp and reach are strongly coordinated in the spatial domain (Haggard and Wing, 1995; Rand et al., 2008). Namely, the distance of the hand from the object when hand opening ceases and hand closing begins (closure distance, usually the point of peak aperture) can be accurately predicted from state estimates of transport velocity, transport acceleration, and aperture.

There is growing interest in contrasting performance of dexterous actions, such as reach-to-grasp, when executed in the physical environment (PE) and VE. In our previous work, we showed that temporal features of reach-to-grasp coordination and the control law governing closure (Mangalam et al., 2021) were preserved in a VE that utilized a reductionist spherical collider representation of the index and thumb and audiovisual feedback-based sensory substitution. However, we noted that movement speed and maximum grip aperture differed between the real environment and VE (Furmanek et al., 2019). These studies utilized only a single set of parameters for the presentation of feedback in the VE, and therefore, the influence of different parameters for representation of the virtual fingers and substitution of haptic feedback is unknown. The goal of this investigation was to test the extent to which the selection feedback parameters influence behavior in the VE. In two studies, we systematically varied parameters related to the sensory modality of haptic sensory substitution (Study 1) and the size of the spherical colliders representing the index-tip and thumb-tip (Study 2) to better understand the influence of these parameters on features of reach-to-grasp performance in VR. In both studies, participants reach to grasp virtual objects at a natural pace in an immersive VE presented *via* a head-mounted display (HMD).

Study 1 was designed to test whether visual, auditory, or audiovisual sensory substitution for haptic feedback of the object properties significantly affects reach-to-grasp kinematics. Participants grasped virtual objects of different sizes and placed them at different distances, where the change in color of the object (visual), tone (auditory), or both (audiovisual) was used to provide the terminal feedback that grasp was completed and achieved successfully. A previous study using spherical colliders to reach to grasp virtual objects reported that audio and audiovisual terminal feedback of the object being grasped resulted in shorter movement times than visual or absent terminal feedback, though there was no effect of terminal feedback on peak aperture (Zahariev and MacKenzie, 2007). While this study had a similar design to our Study 1, it was conducted using stereoscopic glasses to obtain a 3D view of images presented on a 2D display, and the results may not transfer to an HMD-based presentation of VR that presents a more immersive experience and is more commonly used today. Furthermore, no analysis of temporal or spatial reach-to-grasp kinematics was provided, limiting interpretations about the effects of terminal feedback on reach-to-grasp coordination. A more recent study using a robotic-looking virtual hand avatar to reach to grasp and transport virtual objects in an HMD immersive VR setup found that movement time was shorter for visual, compared to auditory or absent, terminal feedback (Canales and Jörg, 2020). Interestingly, participants subjectively preferred audio terminal feedback to other sensory modalities despite the fact that audio feedback produced the slowest movements. The Canales and Jörg study did not measure the kinematics of the movement and therefore interpretation about movement coordination is limited. Based on these studies and our previous work (Furmanek et al., 2019), we expected that the modality of terminal feedback used to signal successful grasp would affect reach-to-grasp kinematics due to uncertainty of contact with an object. Specifically, we hypothesized that, with multimodal (audiovisual) feedback, participants would show (H1.1) greater scaling of aperture to object width and (H1.2) faster completion of the reach-to-grasp task, but (H1.3) the spatiotemporal coordination between the reach and the grasp components of the movement should remain preserved across terminal feedback condition.

To date, no study has systematically examined the impact of the size of the virtual effector on reach-to-grasp kinematics. Study 2 was designed to fill this gap in the literature. Participants used spherical colliders of different diameters to reach to grasp virtual objects of different sizes placed at different distances. Ogawa and coworkers (Ogawa et al., 2018) reported that the size of a virtual avatar hand affects participants' perception of object size in an HMD-based VE, but they did not study reach-to-grasp movements or analyze movement kinematics. Extrapolating from their results, we hypothesized that the size of the spherical collider would affect maximum grip aperture, with smaller colliders predicted to result in larger maximum grip aperture (H2). We specifically used a reduced version of the avatar hand (just two dots representing the thumb and index fingertips) to reduce the number of factors that can potentially affect reach-to-grasp kinematics, such as differences in the shape, color, and texture of a more biological looking hand avatar (Lok et al., 2003; Ogawa et al., 2018). Moreover, the spherical colliders allowed for more precise localization of the fingertips in VE than is typical of anthropomorphic hand avatars (Vosinakis and Koutsabasis, 2018) and eliminated the influence of visuoproprioceptive discrepancies caused by potential tracking or joint angle calibration errors inherent in sensor gloves. Similar reductionist effectors have been successfully used in multiple previous studies for similar reasons (Zahariev and MacKenzie, 2007; Zahariev and Mackenzie, 2008; Furmanek et al., 2019; Mangalam et al., 2021). Furthermore, a recent study where only the target and the richness of hand anthropomorphism (e.g., 2-point, point-dot hand, and full hand) were visible to participants reported that kinematic performance was best when either the minimal (2-point) or enriched hand-like model (skeleton, full) was provided (Sivakumar et al., 2021). Therefore, in the present study, we used simple spheres representing the fingertips to systematically test the effect of collider size on reach-to-grasp behavior.

Study 1 and Study 2 were designed to increase knowledge about how choices for haptic sensory substitution and collider size may affect reach-to-grasp performance in HMD-based VR. This work has the potential to directly impact the design of VR platforms used for commercial, industrial, research, and rehabilitation applications.

2 MATERIALS AND METHODS

2.1 Participants

Ten adults [seven men and three women; $M \pm SD$, age = 21.1 ± 5.88 years; all right-handed (Oldfield et al., 1971)] with no reported muscular, orthopedic, or neurological health concerns voluntarily participated in both studies after providing informed consent approved by the Institutional Review Board (IRB) at Northeastern University. The participant pool was a convenience sample of undergraduate and graduate students. Some participants had previously participated in reach-to-grasp studies in our hf-VE; however, none of the participants reported extensive experience in VR (e.g., gaming and simulations).

2.2 Reach-to-Grasp Task, Virtual Environment, and Kinematic Measurement

Each participant reached to grasp 3D-printed physical objects in the PE and their exact virtual renderings in the haptic-free virtual environment (hf-VE) of three different sizes, small (*width* × *height* × *depth* = 3.6 × 8 × 2.5 cm), medium (5.4 × 8 × 2.5 cm), and large (7.2 × 8 × 2.5 cm), placed at three different distances, near (24 cm), middle (30 cm), and far (36 cm) from the initial position of the fingertips. Objects were rotated along their vertical axis to 75° measured from the horizontal axis to avoid excessive wrist extension. The physical objects were 3D printed using PLA thermoplastic (mass: small: 30 g; medium: 44 g; large: 59 g) and covered with glow-in-the-dark paint.

A commercial HTC Vive Pro, comprised of HMD and an infrared laser emitter unit, was used. The virtual scene was created and rendered in Unity (ver. 5.6, 64 bits, Unity Technologies, San Francisco, CA) with C# as the programming language, running on a computer with Windows 7 Ultimate, 64-bit operating system, an Intel(R) Xenon(R) CPU E5-1630 v3 3.7 GHz, 32 GB RAM, and an NVIDIA Quadro M6000 graphics card. Given the power of the PC and simplicity of the VE, scenes were rendered in less than one frame time (see below). The interpupillary distance in the HMD was individually adjusted to each participant. Objects were displayed in stereovision giving the perception that they were 3D. Participants were asked to confirm that they perceived the object as 3D and that they could distinguish the object's edges, though we did not formally test for stereopsis. Motion tracking of the head was achieved by streaming data from an IMU and laser-based photodiodes embedded in the headset. A detailed description of the HTC Vive's head tracking system is published elsewhere (Niehorster et al., 2017). Position and orientation data provided by the Vive were acquired through

Unity at ~ 90 Hz, the frame rate of the HTC Vive. Prior work has reported that, for large head movements, the average error between the laser-measured position and the position reported by the Vive is less than 1 cm (Luckett, 2018). In our experiment, each participant's head remained relatively stable (the task did not involve extensive head motion) and therefore head tracking inconsistencies were negligible and none of the subjects reported any shifts or jumps in the visual display. An eight-camera motion tracking system (120 Hz, PPT Studio NTM, WorldViz Inc., Santa Barbara, CA) captured the 3D motion of IRED markers attached to the participants' wrist and fingertips. The placement procedure of the IRED markers on the fingertip was as follows: an identical 3D-printed physical object was grasped at the top of its height, and markers were attached to the tops of fingertips in a way that minimized the distance between the object and marker. The centroid of the virtual sphere corresponded to the detected position of the IRED. Note that although data were collected at 120 Hz in the PPT system, acquisition of samples in Unity was limited to ~ 90 Hz, the frame rate of the HTC Vive. Prior to each data collection, the 3D motion capture system was calibrated. This entailed using a standard frame to reset the origin and axes of the 3D space in PPT to match the Unity origin. According to the manufacturer and confirmed by our team when analyzing the residuals during the calibration procedure, the error of the PPT system was less than 1 mm. End-to-end latency, indicating the time between the physical movement of the motion sensor (from PPT) and movement rendered in the virtual scene, was 22 ms (upper bound on the true system latency). This latency was not associated with motion sickness (Stanney, 2002; Barrett, 2004) in a previous publication using a nearly identical system (Niehorster et al., 2017). No participants in our study anecdotally reported symptoms of motion sickness; however, no formal assessment of subjective symptoms of motion sickness was completed. The schedule of trials, virtual renderings of the target object, and timing/triggering of the perturbation were controlled using custom software developed in C#. We recently published two reports showing that spatiotemporal coordination of reach-to-grasp movements is similar in the above described hf-VE compared to that of the real world (Furmanek et al., 2019; Mangalam et al., 2021).

2.3 Procedure and Instructions to Participants

Each participant was seated on a chair with the right arm and hand placed on a table in front of them. At the start position, the thumb and index finger straddled a 1.5 cm wide plastic peg located 12 cm in front and 24 cm to the right of the sternum, with the thumb depressing a switch. Lifting the thumb off the switch marked movement onset. Upon an auditory tone ("beep" signal), the participant reached to grasp the virtual object presented in the HMD, lifted it, held it until it disappeared (3.5 s from movement onset, i.e., the moment the switch was released), and returned their hand to the starting position. Each auditory tone was time jittered within 0.5 s standard deviation from 1 s after trial start (i.e., after the start switch was activated) to avoid participants' adaptation. A custom collision detection algorithm was used to determine when the virtual object was grasped. Each finger was represented by a sphere. When any point on the sphere made contact with any point on the object, it was considered "attached." Once both fingers were "attached" to the object, the object was considered "grasped," and translational movement from the fingers would also move the object. A 1.2 cm error margin, imposed on the distance between the spheres, was used to maintain grasp. If the distance between the spheres increased by more than 1.2 cm from its value at the time the object was "grasped" (e.g., if the fingers opened), the object was no longer considered grasped, the color changed to white, and it would drop to the table. Conversely, if the distance between the spheres decreased by more than 1.2 cm from its value at the time the object was "grasped," the object was considered "overgrasped." An "overgrasped" object would turn white and would remain frozen. If neither error occurred, the object was considered to be grasped successfully, and its color changed to red (visual feedback condition) or a tone sounded (audio condition); see below for details about terminal feedback conditions. 1.2 cm error margin was chosen after extensive piloting of the experiment. In the future, we are planning to systematically check for the effect of the error margin on reach-to-grasp behavior.

Before data collection, each participant was familiarized with the setup and procedure. Familiarization consisted of 30 trials of grasping virtual and physical objects (five trials × three objects, placed at the middle distance) first in PE and then in hf-VE. The participant was instructed to reach and grasp an object at a comfortable speed in the middle along its vertical dimension. Following familiarization, the participant began experimental trials. Further details are provided in the subsequent sections.

To wash out any effect of sensory feedback (Study 1) or collider size (Study 2) on reach-to-grasp coordination, each participant performed a block of reach-to-grasp movements in PE prior to each hf-VE block. The rendering in the virtual scene showed two spheres, representing the thumb and index fingertips, which were visible to the participant. To make the PE condition comparable with regard to what a participant saw, the room was darkened so that the participants could see only the glow-in-the-dark object and the illuminated IRED markers on their fingertips. Overhead lights were turned on and off (after every five trials) to prevent adaptation to the dark. PE trials were used strictly for washout and although data were recorded during these trials, the data were not analyzed nor presented in this manuscript.

2.4 Study 1: Manipulations of Sensory Feedback

Each participant was tested in a single session consisting of 270 trials evenly spread across six blocks of 45 trials, alternating between PE and hf-VE with the first block performed in PE. The participant was given a 2 min break between consecutive blocks. In the three blocks for hf-VE, visual (V), auditory (A), and both visual and auditory [audiovisual (AV)] feedback were provided to indicate that the virtual object had been grasped. In the vision condition, the object turned from blue to red. In the auditory condition, the sound of a click (875 Hz, 50 ms duration) was

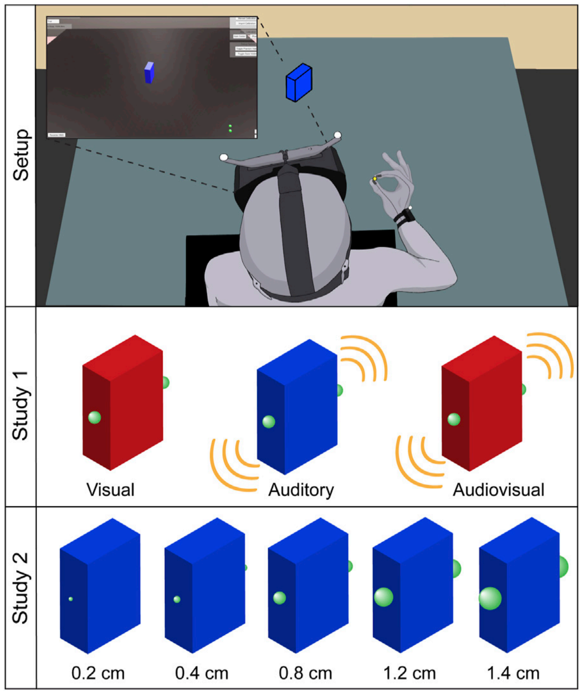

FIGURE 1 | Schematic illustration of the experimental setup and procedure. After wearing an HTC Vive^{TM} head-mounted display (HMD), the participants sat on a chair in front of the experimental rig, with their thumb pressing a start switch (indicated in yellow). IRED markers were attached to the participant's wrist and the tips of the thumb and index finger. An auditory cue—a beep—signaled the participant to reach to grasp the object (small: 3.6 × 2.5 × 8 cm; medium: 5.4 × 2.5 × 8 cm; large: 7.2 × 2.5 × 8 cm), placed at three different distances relative to the switch (near: 24 cm; middle: 30 cm; far: 36 cm). An inset presents the first person scene that appeared in the HMD. Translucent panels containing text in the visual scene were only visible to the experimenter. In Study 1, participants grasped the object with 0.8 cm colliders, and visual, auditory, or audiovisual feedback was provided to signal that the object has been grasped. In Study 2, audiovisual feedback was provided to signal that the object has been grasped, and participants grasped the object with 0.2, 0.4, 0.8, 1.2, and 1.4 cm colliders. In middle and bottom panels, the medium object is presented with the accurate scaling relationship between object dimensions and collider size.

presented. In the audiovisual condition, the object turned from blue to red in addition to the sound of a click (**Figure 1**, top) and remained red until the object disappeared or was released/overgrasped. The collider size remained constant (diameter = 0.8 cm) in each feedback condition. The order of feedback conditions was pseudorandomized across participants. Each condition was collected in a single block that contained 45 trials (three object sizes, three object distances, and five trials per size-distance pair). Objects in each block were presented in the same order [small-near (five trials), small-middle (five trials), and small-far (five trials); medium-near (five trials), medium-middle (five trials), and medium-far (five trials); large-near (five trials), large-middle (five trials), and large-far (five trials)]. Each block of virtual grasping was preceded by an identical block of grasping physical objects to wash out possible carryover effects from the previous hf-VE block.

2.5 Study 2: Manipulations of Collider Size

Each participant was tested in a single session consisting of 450 trials evenly spread across ten blocks of 45 trials, alternating between PE and hf-VE with the first block performed in PE. The participant was given a 2 min break between consecutive blocks. In the five hf-VE blocks, we manipulated the collider size to be 0.2, 0.4, 0.8, 1.2, or 1.4 cm (**Figure 1**, bottom). Collider size was constant for all trials within a block. The order that collider size blocks were presented was pseudorandomized across participants. Each block contained 45 trials (three object sizes, three object distances, and five trials per size-distance pair). Objects in each block were presented in the same order [small-near (five trials), small-middle (five trials), and small-far (five trials); medium-near (five trials), medium-middle (five trials), and medium-far (five trials); large-near (five trials), large-middle (five trials), and large-far (five trials)]. Each block of virtual grasping was preceded by an identical block of grasping physical objects to wash out possible carryover effects from the previous hf-VE block.

2.6 Kinematic Processing

All kinematic data were analyzed offline using custom MATLAB routines (Mathworks Inc., Natick, MA). For each trial, time series data for the planar motion of the markers in the x- and y-coordinates were cropped from movement onset (the moment the switch was released) to movement offset (the moment the collision detection criterion was met). Transport distance (i.e., the straight-line distance of the wrist marker from the starting position in the transverse plane) and aperture (the straight-line distance between the thumb and index finger markers in the transverse plane) trajectories were computed for each trial. The first derivative of transport displacement and aperture was computed to obtain the velocity profiles for kinematic feature extraction. All time series were filtered at 6 Hz using a fourth-order low-pass Butterworth filter. In line with our past data processing protocols, trials in which participants did not move or lifted their fingers off the starting switch not in the process of making a goal-directed action toward the object were excluded from the analysis. Excluded trials comprised $< 3\%$ of trials in any given condition.

Additionally, we also computed the time series for size-normalized aperture. The rationale for this normalization was twofold. First, markers were attached to the dorsum of the digits (on the nail) to avoid interference with grasping. Second, in hf-VE, the collider's relative sizes and the target object might influence the grasp. For instance, a larger collider might lead to a small object being perceived disproportionately smaller than a large object. Normalizing peak aperture by object size allowed us to examine any effect of such perceptual discrepancy on the grasp.

For each trial, the following kinematic features, units in parentheses, were extracted using the filtered time series data:

- Movement time (ms): duration from movement onset to movement offset.
- Peak aperture (cm): maximum distance between the fingertip markers. Peak aperture also marked the

initiation of closure or closure onset (henceforth, CO), which we refer to as aperture at CO.
- Size-normalized peak aperture: peak aperture normalized by the target object width.
- Time to peak aperture (ms): time from movement onset to peak aperture.
- Closure distance (cm): distance between the wrist's position at CO and the object's center.
- Peak transport velocity (cm/s): maximum velocity of the wrist marker.
- Time to peak transport velocity (ms): time from movement onset to maximum velocity of the wrist marker.
- Transport velocity at CO (cm/s): velocity of the wrist marker at the time of CO.

Movement time was used to examine the global effect of condition manipulations on reach-to-grasp movements. Peak aperture, time to peak aperture, and size-normalized peak aperture were used to examine the effect on the grasp component. Likewise, peak transport velocity and time to peak transport velocity were used to examine the effect on the transport component. Finally, time to peak transport velocity and time to peak aperture as well as transport velocity at CO and closure distance were used to examine the effects of task manipulations on reach-to-grasp coordination (Furmanek et al., 2019; Mangalam et al., 2021).

2.7 Statistical Analysis

All analyses were initially performed at the trial level to compute means for each subject. Subjects' means were then submitted to analysis of variance for group-level statistics. 3 × 3 × 3 repeated measures analyses of variance (rm-ANOVAs) with within-subject factors of sensory feedback (visual, auditory, and audiovisual), object size (small, medium, and large), and object distance (near, middle, and far) were used to evaluate the effects on each kinematic variable in Study 1. 5 × 3 × 3 rm-ANOVAs with within-subject factors of collider size (0.2, 0.4, 0.8, 1.2, and 1.4), object size (small, medium, and large), and object distance (near, middle, and far) were used to evaluate the effects on each kinematic variable separately in Study 2. In most cases, the data met assumptions for normality, homogeneity of variance, and sphericity. When an assumption of sphericity was not met, a Greenhouse-Geisser correction was applied. All tests were performed in Statistica (ver. 13, Dell Inc.). Each test statistic was considered significant at the two-tailed alpha level of 0.05. All effect sizes are reported as partial eta-squared (η^2).

We used linear mixed-effects (LME) models to test the relationship between time to peak transport velocity and time to peak aperture and between closure transport velocity at CO and closure distance, in both Studies 1 and 2. The same LMEs also tested whether and how the respective relationship was influenced by sensory feedback in Study 1 and collider size in Study 2. In LMEs for Study 1, sensory feedback served as a categorical independent variable with three levels: visual, auditory, and audiovisual. The "visual" feedback served as the reference level. In LMEs for Study 2, collider size served as a continuous independent variable. In each model, participant identity was treated as a random effect. Both models were fit using the lmer() function in the package *lme4* (Bates et al., 2014) for *R* (Team R. C., 2013). Approximate effect sizes for LMEs were computed using the omega_squared() function in the package *effectsize* (Ben-Shachar et al., 2021) for *R*. Coefficients were considered significant at the alpha level of 0.05.

3 RESULTS

3.1 Study 1: Effects of Sensory Feedback on Reach-to-Grasp Movements

Figure 2A shows the trajectories of the mean 2D position of the wrist, thumb, and index finger corresponding to each sensory feedback condition for a representative participant (averaged across all trials) for the medium object placed at the middle distance. **Figure 2B** shows the mean transport velocity and aperture profiles obtained from the trajectories shown in **Figure 2A**. Notice that, in both figures, the curves for the three feedback conditions entirely eclipse each other, indicating that sensory feedback affected neither the wrist, thumb, and index finger trajectories nor the transport velocity and aperture profiles. **Figure 3** shows the phase relationship between transport velocity and size-normalized aperture (Furmanek et al., 2019). An almost invariant location of peak transport velocity and peak aperture, which mark the onset of the shaping phase and the closure phase, respectively, indicates that this phase relationship did not vary across feedback conditions.

An rm-ANOVA revealed that movement time did not differ among the three types of sensory feedback ($p > 0.05$; **Table 1**). As expected, movement time differed across objects placed at different distances ($F2,18 = 36.71$, $p < 0.001$). Bonferroni's post hoc tests revealed that movement time was longer for more distant objects (middle vs. near: 48 ± 10 ms, $p < 0.001$; far vs. near: 87 ± 10 ms, $p < 0.001$; far vs. middle: 38 ± 10 ms, $p = 0.004$; **Figure 4A**). Neither the main effect of object size nor any of the interaction effects of sensory feedback, object distance, and object size was significant ($p > 0.05$, **Table 1**).

Neither sensory feedback nor object distance affected any kinematic variable related to the grasp component: peak aperture and size-normalized peak aperture ($p > 0.05$; **Table 1**). With respect to these variables, peak aperture differed across objects of different sizes ($F2,18 = 232.39$, $p < 0.001$), as did size-normalized peak aperture ($F1,9.2 = 34.08$, $p < 0.001$). Bonferroni's post hoc tests revealed that peak aperture was larger for a larger object (medium vs. small: 1.3 ± 0.1 cm, $p < 0.001$; large vs. small: 2.7 ± 0.1 cm, $p < 0.001$; large vs. medium: 1 < 0.3 ± 0.1 ms, $p < 0.001$; **Figure 4B**) confirming that the grasp was scaled to object size. However, the size-normalized peak aperture was larger for a smaller object (medium vs. small: −1.5 ± 0.3, $p < 0.001$; large vs. small: −2.0 ± 0.3, $p < 0.001$, **Figure 4C**), suggesting that participants had a greater aperture overshoot for smaller objects, consistent with past results (Meulenbroek et al., 2001; Furmanek et al., 2019). None of the interaction effects of sensory feedback, object distance, and object size on peak aperture or size-normalized peak aperture were significant ($p > 0.05$; **Table 1**).

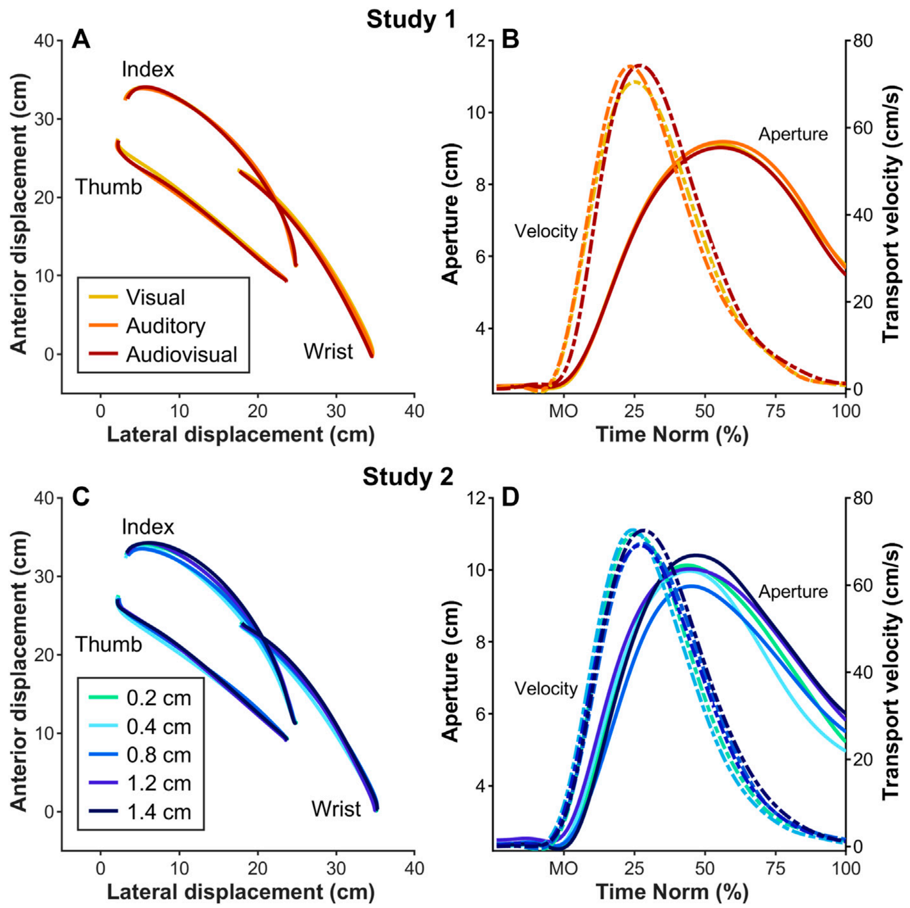

FIGURE 2 | Mean trajectories for a representative participant showing reach-to-grasp kinematics for different sensory feedback and collider size. *Study 1.* **(A)** Marker trajectories for the wrist, thumb, and index finger across different conditions of sensory feedback. **(B)** Time-normalized aperture (solid lines) and transport velocity (dashed-dotted lines) profiles across different conditions of sensory feedback. *Study 2.* **(C)** Marker trajectories for the wrist, thumb, and index finger across different collider sizes. **(D)** Time-normalized aperture (solid lines) and transport velocity (dash-dotted lines) profiles across different collider sizes.

Sensory feedback did not affect any variable related to the transport component: peak transport velocity, time to peak transport velocity, and transport velocity at CO ($p > 0.05$; **Table 1**). As expected, peak transport velocity ($F1.1,10.1 = 239.96$, $p < 0.001$), time to peak transport velocity ($F2,18 = 33.00$, $p < 0.001$), and transport velocity at CO ($F2,18 = 5.11$, $p < 0.010$) differed across objects placed at different distances. Bonferroni's post hoc tests revealed that the values were larger for a more distant object for peak transport velocity (middle vs. near: 12.6 ± 1.1 cm/s, $p < 0.001$; far vs. near: 23.6 ± 1.1 cm/s, $p < 0.001$; far vs. middle: 11.0 ± 1.1 cm/s, $p < 0.001$), time to peak transport velocity (middle vs. near: 19 ± 3 ms, $p < 0.001$; far vs. near: 25 ± 3 cm/s, $p < 0.001$), and transport velocity at CO (far vs. near: 4.3 ± 1.4 cm/s, $p = 0.006$). Neither the main effect to object size nor any of the interaction effects of sensory feedback, object distance, and object size on any of these variables was significant ($p > 0.05$). Furthermore, transport velocity at CO differed across objects of different sizes ($F2,18 = 9.42$, $p < 0.001$). Bonferroni's post hoc tests revealed that transport velocity at CO was lower for a smaller object (large vs. small: 7.8 ± 1.8 cm/s, $p = 0.001$). Otherwise, neither the main effect of object size nor any of the interaction effects of sensory feedback, object distance, and object size was significant for any of these variables ($p > 0.05$; **Table 1**).

To investigate whether reach-to-grasp coordination was influenced by visual, auditory, and audiovisual feedback, LMEs were performed to test the relationship between time to peak transport velocity and time to peak aperture and between closure transport velocity at CO and closure distance, and how it was influenced by sensory feedback. Time to peak aperture increased with time to peak transport velocity ($B = 1.23 \pm 0.16$, $t = 7.95$, $p < 0.001$; **Figure 7A**). The observed increase in time to peak aperture with an increase in time to peak transport velocity did not differ between the three types of sensory feedback ($p > 0.05$; **Table 2**). Likewise, closure distance increased with transport velocity at CO ($B = 0.15 \pm 0.0057$, $t = 26.50$, $p < 0.001$; **Figure 7B**). The observed increase in closure distance with an increase in transport velocity at CO did not differ between the three types of sensory feedback ($p > 0.05$; **Table 2**). Together, these results indicate that sensory feedback signaling that the

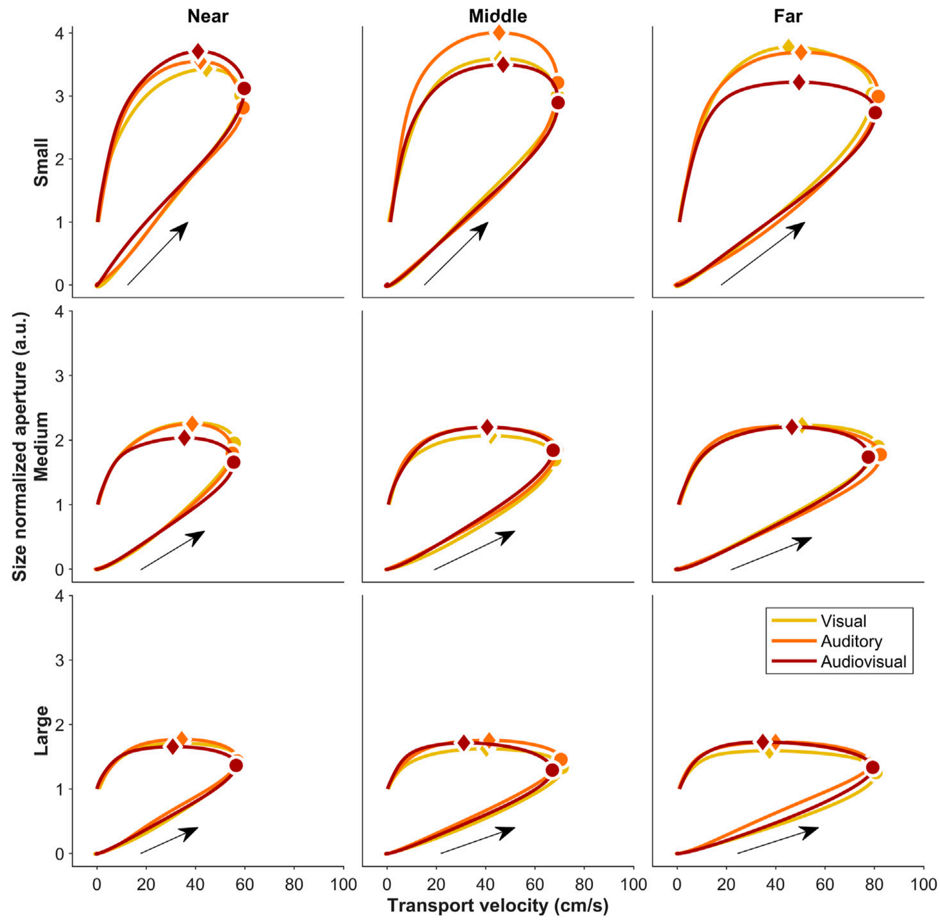

FIGURE 3 | Study 1. Phase plots of size-normalized aperture vs. transport velocity for each condition of sensory feedback for a representative participant. Diamonds and circles indicate size-normalized peak aperture and peak transport velocity, respectively. Black arrows indicate the progression of reach-to-grasp movement.

object had been grasped did not affect the coordination between the transport and aperture components, including the initiation of closure based on the state estimate of transport velocity.

In summary, these results confirm the known effects of object size and object distance on variables related to the aperture and transport components, respectively (Paulignan et al., 1991a; Paulignan et al., 1991b). However, each type of sensory feedback—visual, auditory, or audiovisual—is equally provided for successful reach-to-grasp.

3.2 Study 2: Effects of Collider Size on Reach-to-Grasp Movements

Figure 2C shows the trajectories of the mean 2D position of the wrist, thumb, and index finger corresponding to each collider size condition for a representative participant (averaged across all trials) for the medium object placed at the middle distance. **Figure 2D** shows mean transport velocity and aperture profiles obtained from the trajectories shown in **Figure 2C**. Notice that, in both figures, curves for the five collider sizes show noticeable differences. **Figure 5** shows the phase relationship between transport velocity and size-normalized aperture. Notice that the magnitude of size-normalized peak aperture reduces with collider size and disproportionately more for a smaller and a more distant object, but it occurs at about the same transport velocity.

An rm-ANOVA revealed a significant main effect of collider size on movement time ($F4{,}36 = 2.87$, $p < 0.030$, **Table 3**). However, Bonferroni's post hoc tests failed to identify any pairwise differences for different collider sizes ($p > 0.05$, **Figure 6A**). As expected, movement time differed across objects placed at different distances ($F1.1{,}10 = 59.70$, $p < 0.001$). Bonferroni's post hoc tests revealed that movement time was larger for a more distantly placed object (middle vs. near: 49 ± 9 ms, $p < 0.001$; far vs. near: 97 ± 9 ms, $p < 0.001$; far vs. middle: 48 ± 9 ms, $p = 0.004$). Neither the main effect of object size nor any interaction effects of collider size, object distance, and object size were significant ($p > 0.05$).

Neither collider size nor object distance affected peak aperture ($p > 0.05$; **Figure 6B**). As expected, aperture differed across objects of different sizes ($F1.1,\ 10.4 = 183.04$, $p < 0.001$). Bonferroni's post hoc tests revealed that peak aperture was

TABLE 1 | Outcomes of 3 × 3 × 3 rm-ANOVAs examining the effects of sensory feedback (visual, auditory, and audiovisual), object size (small, medium, and large), and object distance (near, middle, and far) on each kinematic variable in Study 1.

Variables	Sensory feedback (SF)	Object size (OS)	Object distance (OD)	Interactions
MT (ms)	NS	NS	$F_{2,18}$ = 36.71 p < 0.001 η^2 = 0.80	NS
PA (cm)	NS	$F_{2,18}$ = 232.39 p < 0.001 η^2 = 0.96	NS	NS
SN-PA (a.u.)	NS	$F_{1,9.2}$ = 34.08 p < 0.001 η^2 = 0.79	NS	NS
PV (cm/s)	NS	NS	$F_{1.1,10.1}$ = 239.96 p < 0.001 η^2 = 0.96	NS
T-PV (ms)	NS	NS	$F_{2,18}$ = 33.00 p < 0.001 η^2 = 0.78	NS
TV-CO (cm/s)	NS	$F_{2,18}$ = 9.42 p < 0.001 η^2 = 0.51	$F_{2,18}$ = 5.11 p < 0.010 η^2 = 0.36	NS

MT: movement time, PA: peak aperture, SN-PA: size-normalized peak aperture, PV: peak transport velocity, T-PV: time to peak transport velocity, and TV-CO: transport velocity at closure onset. NS: not significant.

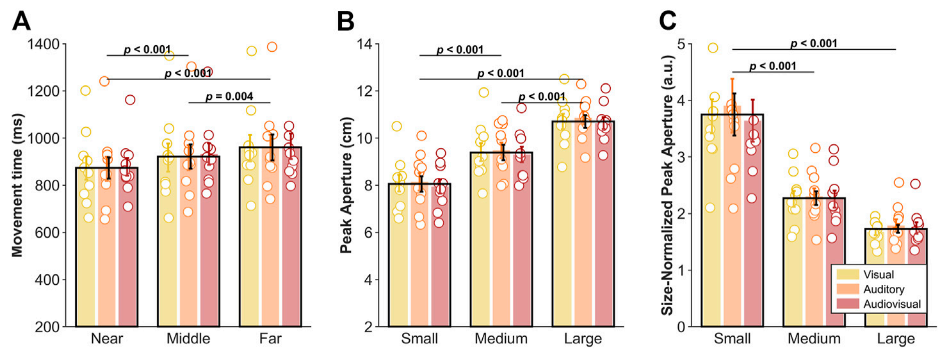

FIGURE 4 | Study 1. Effects of **(A)** object distance on movement time, **(B)** object size on peak aperture, and **(C)** object size on size-normalized peak aperture. Error bars indicate ±1*SEM* (*n* = 10). Data calculated across all levels of sensory feedback for each participant.

TABLE 2 | Summary of linear mixed-effects (LME) models in Study 1.

Effects	B	± 1SE	t	p	η^2
Time to peak aperture					
Intercept	139.44	50.85	2.74	0.0068	–
TPV	1.23	0.16	7.95	0.0000	0.25
Auditory	14.96	45.47	0.33	0.7424	0.004
Audiovisual	40.74	44.44	0.92	0.3602	0.004
TPV × auditory	−0.05	0.15	−0.31	0.7542	0.004
TPV × audiovisual	−0.13	0.15	−0.87	0.3869	0.004
Closure distance					
Intercept	−0.82	0.38	−2.19	0.0378	–
TV-CO	0.15	0.01	26.50	0.0000	0.79
Auditory	−0.23	0.27	−0.87	0.3880	0.001
Audiovisual	0.18	0.27	0.68	0.4950	0.001
TV-CO × auditory	0.00	0.01	0.77	0.4413	0.003
TV-CO × audiovisual	−0.01	0.01	−0.96	0.3370	0.003

larger for a larger object (medium vs. small: 1.2 ± 0.1 cm, $p < 0.001$; large vs. small: 2.5 ± 0.1 cm, $p < 0.001$; large vs. medium: 1.3 ± 0.1 ms, $p < 0.001$) confirming that the grasp was scaled to object size. None of the interaction effects of collider size, object distance, and object size on peak aperture was significant ($p > 0.05$).

Size-normalized peak aperture differed across collider sizes (F4, 36 = 4.42, p = 0.005). Bonferroni's post hoc tests revealed that size-normalized peak aperture was smaller for a larger collider (1.4 vs. 0.2 cm colliders: −0.6 ± 0.2, p = 0.012; 1.4 vs. 0.4 cm colliders: −0.5 ± 0.2, p = 0.043; 1.4 vs. 0.8 cm colliders: −0.5 ± 0.2, p = 0.045, **Figure 6C**). Size-normalized peak aperture also differed across objects of different sizes (F4, 36 = 64.60, $p < 0.005$). Bonferroni's post hoc tests revealed that, as opposed to peak aperture, size-normalized peak aperture was larger for a smaller object (medium vs. small: −1.5 ± 0.2,

TABLE 3 | Outcomes of 5 × 3 × 3 rm-ANOVAs examining the effects of collider size (0.2, 0.4, 0.8, 1.2, and 1.4), object size (small, medium, and large), and object distance (near, middle, and far) on each kinematic variable in Study 2.

Variables	Collider size (CS)	Object size (OS)	Object distance (OD)	Interactions
MT (ms)	$F_{4,36} = 2.87$ $p < 0.030$ $\eta^2 = 0.24$	NS	$F_{1.1,10} = 59.70$ $p < 0.001$ $\eta^2 = 0.87$	NS
PA (cm)	NS	$F_{1.1,10.4} = 183.04$ $p < 0.001$ $\eta^2 = 0.95$	NS	OS×OD, $F_{4,36} = 9.19$ $p < 0.001$ $\eta^2 = 0.5$
SN-PA (a.u.)	$F_{4,36} = 4.42$ $p = 0.005$ $\eta^2 = 0.33$	$F_{1.3,115} = 64.60$ $p < 0.005$ $\eta^2 = 0.88$	NS	NS
PV (cm/s)	NS	$F_{2,18} = 11.76$ $p < 0.001$ $\eta^2 = 0.57$	$F_{1.1,9.7} = 227.51$ $p < 0.001$ $\eta^2 = 0.96$	OS×OD, $F_{4,36} = 5.35$ $p < 0.001$ $\eta^2 = 0.37$
T-PV (ms)	$F_{4,36} = 4.57$ $p = 0.004$ $\eta^2 = 0.34$	NS	$F_{2,18} = 31.77$ $p < 0.001$ $\eta^2 = 0.78$	NS
TV-CO (cm/s)	NS	$F_{2,18} = 38.12$ $p < 0.001$ $\eta^2 = 0.81$	$F_{1.1,10.2} = 14.42$ $p < 0.002$ $\eta^2 = 0.61$	NS

MT: movement time, PA: peak aperture, SN-PA: size-normalized peak aperture, PV: peak transport velocity, T-PV: time to peak transport velocity, and TV-CO: transport velocity at closure onset. NS: not significant.

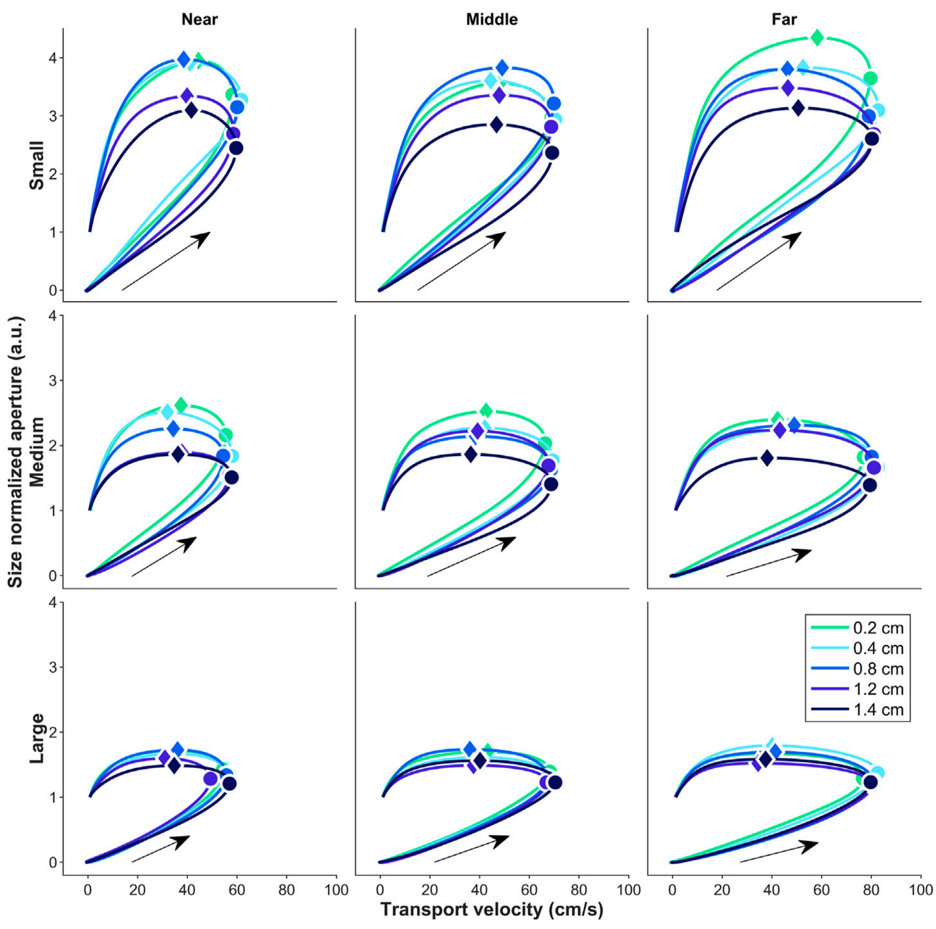

FIGURE 5 | Study 2. Phase plots of size-normalized aperture vs. transport velocity for each collider size for a representative participant. Diamonds and circles indicate size-normalized peak aperture and peak transport velocity, respectively. Black arrows indicate the progression of reach-to-grasp movement.

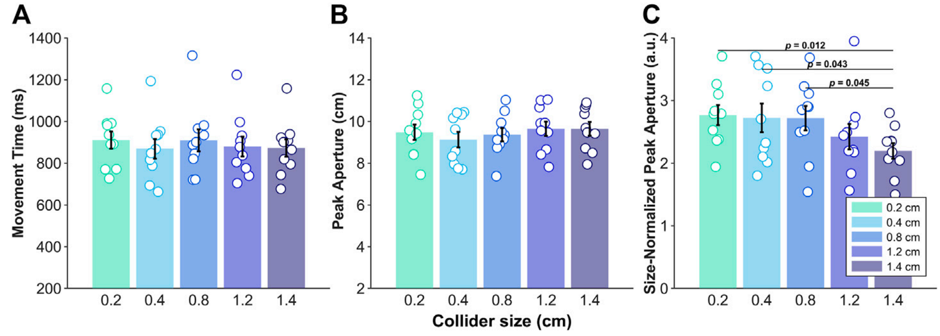

FIGURE 6 | Study 2. Effects of collider size on **(A)** movement time, **(B)** peak aperture, and **(C)** size-normalized peak aperture. Error bars indicate ± 1*SEM* (*n* = 10). Data calculated across all levels of object size and object distance for each participant.

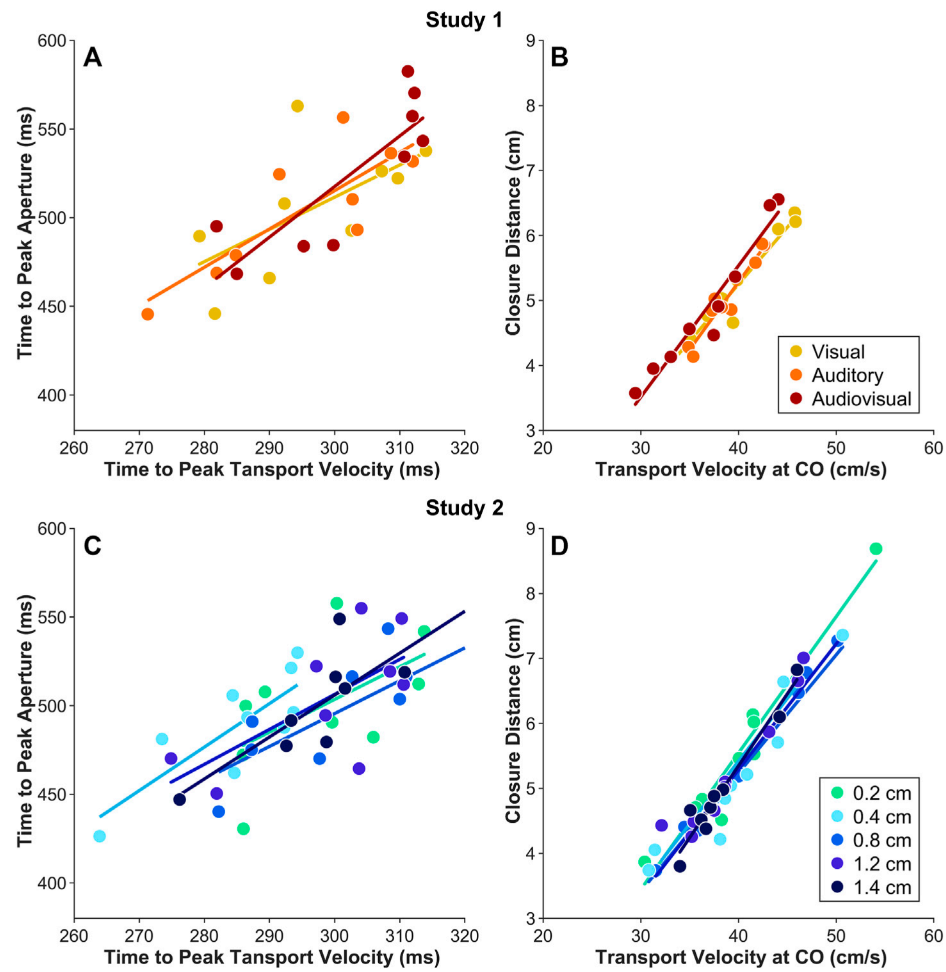

FIGURE 7 | Effects of sensory feedback (Study 1, **A** & **B**) and collider size (Study 2, **C** & **D**) on reach-to-grasp coordination. **(A,C)** Temporal coordination: time to peak transport velocity vs. time to peak aperture. **(B,D)** Spatial coordination: transport velocity at CO vs. closure distance. Manipulation of sensory feedback and collider size did not alter reach-to-grasp coordination, indicating that the state-of-the-art hf-VE can support stable reach-to-grasp movement coordination patterns.

$p < 0.001$; large vs. small: −2.1 ± 0.2, $p < 0.001$; large vs. medium: −0.6 ± 0.2, $p = 0.013$), confirming that the grasp was scaled to object size. Neither the main effect of object distance nor any of the interaction effects of collider size, object distance, and object size on size-normalized peak aperture was significant ($p > 0.05$; **Table 3**).

TABLE 4 | Summary of LME models in Study 2.

Effects	B	± 1SE	t	p	η^2
Time to peak aperture					
Intercept	254.08	39.69	6.40	0.0000	–
TPV	0.83	0.11	7.34	0.0000	0.10
Collider size	–35.93	26.48	–1.36	0.1760	0.001
TPV × collider size	0.12	0.09	1.36	0.1750	0.001
Closure distance					
Intercept	–1.10	0.43	–2.58	0.0168	–
TV-CO	0.17	0.01	27.37	0.0000	0.62
Collider size	–0.06	0.22	–0.28	0.7792	0.002
TV-CO × collider size	0.00	0.01	–0.94	0.3492	0.0002

The only significant main effect of collider size was observed on time to peak transport velocity ($F4, 36 = 4.57$, $p = 0.004$). Bonferroni's post hoc tests revealed that time to peak transport velocity was larger for a larger collider (0.8 vs. 0.4 cm colliders: 16 ± 4 ms, $p = 0.007$; 1.2 vs. 0.4 cm colliders: 14 ± 4 ms, $p = 0.027$; 1.6 vs. 0.4 cm colliders: 15 ± 4 ms, $p = 0.015$). With respect to these variables, peak transport velocity ($F1.1,9.7 = 227.51$, $p < 0.001$), time to peak transport velocity ($F2, 18 = 31.77$, $p < 0.001$), and transport velocity at CO ($F1.1, 10.2 = 14.42$, $p < 0.001$) differed across objects placed at different distances. Bonferroni's post hoc tests revealed that the values were larger for a more distant object for peak transport velocity (middle vs. near: 12.5 ± 1.1 cm/s, $p < 0.001$; far vs. near: 24.1 ± 1.1 cm/s, $p < 0.001$; far vs. middle: 11.6 ± 1.1 cm/s, $p < 0.001$), time to peak transport velocity (middle vs. near: 15 ± 3 ms, $p < 0.001$; far vs. near: 23 ± 3 cm/s, $p < 0.001$; middle vs. near: 8 ± 3 ms, $p = 0.044$), and transport velocity at CO (middle vs. near: 4.8 ± 1.5 cm/s, $p = 0.013$; far vs. near: 7.9 ± 1.5 cm/s, $p < 0.001$).

To investigate whether reach-to-grasp coordination was influenced by collider size, LMEs were performed to test the relationship between time to peak transport velocity and time to peak aperture and between closure transport velocity at CO and closure distance and how it was influenced by collider size. Time to peak aperture increased with time to peak transport velocity ($B = 0.83 \pm 0.11$, $t = 7.34$, $p < 0.001$; **Figure 7C**). The observed increase in time to peak aperture with an increase in time to peak transport velocity was not affected by collider size ($p > 0.05$; **Table 4**). Likewise, closure distance increased with transport velocity at CO ($B = 0.17 \pm 0.0061$, $t = 27.37$, $p < 0.001$; **Figure 7D**). The observed increase in closure distance with an increase in transport velocity at CO was not affected by collider size ($p > 0.05$; **Table 4**). Together, these results indicate that collider size did not affect the coordination between the transport and aperture components, including the initiation of closure based on the state estimate of transport velocity.

In summary, these results further confirm the known effects of object size and object distance on variables related to the aperture and transport components, respectively (Paulignan et al., 1991a; Paulignan et al., 1991b). Most importantly, we show that collider size also affects properties of the grasp relative to the object, specifically, a larger collider prompts a proportionally small aperture. Nonetheless, it appears that collider size has no bearing on reach-to-grasp coordination.

4 DISCUSSION

We investigated the effects of sensory feedback mode (Study 1) and collider size (Study 2) on the coordination of reach-to-grasp movements in hf-VE. Contrary to our expectation (H1), we found that visual, auditory, and audiovisual feedback did not differentially impact key features of reach-to-grasp kinematics in the absence of terminal haptic feedback. In Study 2, larger colliders led to a smaller size-normalized peak aperture (H2) suggesting a possible influence of spherical collider size on the perception of virtual object size and motor planning of reach-to-grasp. Critically, reach-to-grasp spatiotemporal coordination patterns were robust to manipulations of sensory modality and for haptic sensory substitution and spherical collider size.

4.1 Manipulations of Sensory Substitution

In Study 1, we did not observe any changes in the transport and aperture kinematics or in the reach-to-grasp coordination, as a function due to the type of sensory substitution that was provided (visual, auditory, or audiovisual) to indicate that the object had been grasped in the absence of haptic feedback about object properties. Our data did confirm the known effects of object size and object distance on variables related to the aperture and transport components, respectively (Paulignan et al., 1991a; Paulignan et al., 1991b), indicating that variation in reach-to-grasp patterns with respect to object properties in our hf-VE is comparable to that found in the real world as previously indicated in Furmanek et al. (2019). While many studies have explored the role of sensory substitution of haptic feedback in VR (Sikström et al., 2016; Cooper et al., 2018), few studies have investigated the effect of sensory substitution for haptic feedback, specifically in the context of reach-to-grasp movements. One study that used simple spherical colliders for grasping reported faster movement time when sensory substitution for haptic feedback was provided with audio and audiovisual cues compared to visual or absent cues that the object was grasped (Zahariev and MacKenzie, 2007). Our findings that there were no differences in movement kinematics for different types of haptic sensory substitution conditions do not support these past findings, though differences in the outcomes may be explained, in part, by the VR technology utilized. For example, in Zahariev and MacKenzie (2007), participants grasped mirror reflections of computer-generated projections of objects. Such setups have lower fidelity of object rendering than what is typical of HMD-VR and might result in greater salience to auditory feedback. In a more recent study using HMD-VR, participants performed reach-to-grasp movements as part of a pick and place task in less time with visual compared to auditory sensory substitution but interestingly indicated a preference for auditory cues that the object was grasped (Canales and Jörg, 2020). Notably, differences between audio, visual, and audiovisual feedback were small, and since reach-to-grasp kinematics were not presented, interpretations as to why the movements were slower with audio feedback were not possible to make. In an immersive hf-VE like ours, participants might not have had to rely on one sensory modality over the other and hence did not show differences in reach-to-grasp coordination based on visual, auditory, and audiovisual feedback. Furthermore, the fact that we did not observe differences in movement kinematics and spatiotemporal reach-to-grasp coordination (**Figures 7A,B**) suggests that, in a high-fidelity VR environment, the choice of modality for sensory substitution for haptic feedback may have relatively little bearing on behavior. We speculate that, with high-fidelity feedback of the hand-object interaction, visual feedback of the hand-object collision, rather than explicit feedback in the form of overt sensory substitution, may govern behavior.

The finding that visual information may be sufficient for haptic-free grasping is in agreement with the interesting line of research using a haptic-free robotic system. For instance, Meccariello and others (Meccariello et al., 2016) showed that experienced surgeons perform conventional suturing faster and more accurately than nonexperts when only visual information was used. It has been proposed that experienced surgeons may create a perception of haptic feedback during haptic-free robotic surgery based on visual information and previously learned haptic sensations (Hagen et al., 2008). This suggests that haptic feedback may be needed during skill acquisition, but not necessary for practiced movement.

Another parsimonious explanation for why we did not observe between-condition differences of sensory feedback type on grasp kinematics is related to the study design. As opposed to Zahariev and Mackenzie (2007) and Zahariev and Mackenzie (2008), who randomized the order of object size trials, our participants performed reach-to-grasp actions to each object in a blocked manner (i.e., all trials for each object size-distance pair were completed consecutively within each block). Thus, in our study, subjects' prior experience—specifically, the proprioceptively perceived final aperture—might have made reliance on explicit feedback of grasp less necessary. Indeed, the calibration of the current reach-to-grasp movement based on past movements is well documented (Gentilucci et al., 1995; Säfström and Edin, 2004; Säfström and Edin, 2005; Bingham et al., 2007; Mon-Williams and Bingham, 2007; Coats et al., 2008; Säfström and Edin, 2008; Foster et al., 2011). Finally, the availability of continuous online feedback of the target object and colliders might have also reduced reliance on sensory feedback (Zahariev and MacKenzie, 2007; Zahariev and Mackenzie, 2008; Volcic and Domini, 2014). The present study was not designed to test such a hypothesis, but future work can explicitly investigate whether reliance on different modalities of terminal sensory feedback may be stronger in a randomized design, when anticipation and planning are less dependable.

4.2 Manipulations of Collider Size

In Study 2, there was a significant main effect of collider size for movement time, time to peak transport velocity, and size-normalized peak aperture indicating that collider size modified key features of the reach-to-grasp movement. It is likely that the collider size altered the perception of object size, an object might be perceived to be smaller when using a larger collider, and that this altered perception might have affected the planning of reach-to-grasp movements. Indeed, previous studies have shown that the hand avatar may act as a metric to scale the intrinsic object properties (e.g., object size) (Linkenauger et al., 2011; Linkenauger et al., 2013; Ogawa et al., 2017; Ogawa et al., 2018; Lin et al., 2019). Interestingly, Ogawa et al. (2017) found that perception of object size was affected by the realism of the avatar, with a biological avatar showing a greater effect on object size perception than an abstract avatar such as what was used in our study. However, in that study participants did not grasp the object; the task was simply to carry the virtual cube object on an open avatar palm. It may therefore be concluded that the effect of avatar size on perception is likely mediated by the requirements of the task, and the use of avatar size as a means to scale the dimension of the intrinsic object properties is more sensitive when the avatar is used to actually grasp the object. One caveat to our finding is that a collider size by object size interaction was not observed. If collider size caused a linear scaling of the perception of object size, then a collider size by object size interaction would be expected as the change in the ratio of collider size to object size will be different for different object sizes. Hand size manipulations do not affect the perceived size of objects that are too big to be grasped, suggesting that hand size may only be used as a scaling mechanism when the object affords the relevant action, in this case, grasping (Linkenauger et al., 2011), providing further evidence of nonlinearities in the use of the hand avatar as a "perceptual ruler." Therefore, our findings indicate that either the scaling of perception of object size by collider size is nonlinear or the changes we observed arise from different explicit strategies for different colliders independent of perception. Future research will test these competing hypotheses.

Assuming that collider size did in fact influence the perception of object size, it follows that the size of the colliders might have had a similar effect on altering the perceptual scaling of object distance. This interpretation provides a possible explanation for the significant main effect of collider size on time to peak transport velocity. However, given that the ratio of collider size to object distance was much smaller than the ratio of collider size to object size, we think that perceptual effects on distance were probably negligible, at least relative to the perceptual effects on object size. We therefore offer an alternative explanation for the scaling of peak transport velocity and associated movement time, with different collider sizes. If collider size affected the planning of aperture overshoot, as evidenced by the main effect of size-normalized peak aperture, then we may assume that this was also incorporated into the planning of transport to maintain the spatiotemporal coordination of reach-to-grasp. Our data indicate that this may be the case, as both temporal (the relationship between time to peak transport velocity and time to peak aperture) and spatial (the relationship between transport velocity at CO and closure distance) aspects of coordination were not influenced by collider size (**Figures 7C,D**).

Agnostic to whether the effects of the colliders on aperture profiles were perceptual or strategic, we surmise that these effects were present at the beginning of the movement to ensure that the coordination of the reach and grasp component was not disrupted. Preservation of reach-to-grasp coordination as the primary goal of reach-to-grasp movements is something we have observed in our previous work (Furmanek et al., 2019; Mangalam et al., 2021). The block nature of our design likely facilitated the described effect on planning; however, we do not believe that proprioceptive memory had a large influence on the effects observed in Study 2. If proprioceptive memory did influence behavior, we can assume that it would be equal across all collider sizes and therefore cannot explain behavioral differences across collider sizes. Future research should test whether the observations here hold if object size and distance are randomized.

Our result that larger colliders led to a smaller size-normalized peak aperture can also be framed using the equilibrium point hypothesis (EPH) (Feldman, 1986). In this framework, the peak aperture at a location near the object may be considered a key point in the referent trajectory driving the limb and finger movements (Weiss and Jeannerod, 1998). Given the evidence that the referent configuration for a reach-to-grasp action is specified depending on the object shape, localization, and orientation to define a position-dimensional variable, threshold muscle length (Yang and Feldman, 2010), it is possible that collider size may also influence the referent configuration. One possibility is that collider size may influence the perceived force needed to grasp the object (Pilon et al., 2007) despite the virtual object having no physical properties. Future studies may be specifically designed to test this hypothesis for hf-VE.

4.3 Limitations

Our studies had several limitations. Data were collected from only ten participants limiting the generalization of our findings and potentially exposing us to type 2 error if a certain outcome measure effect size is small. The sample involved only three female participants making it difficult to understand if there may be sex-dependent differences in reach-to-grasp performance, particularly in light of recent evidence that VR may be experienced differently between male and female participants (Munafo et al., 2017; Curry et al., 2020). We used a simple hand avatar rendering of spheres to represent only the tips of the thumb and index finger, and the results of this study may not extrapolate to more anthropomorphic avatars. Our VE was simple comprising only the table, object to be grasped, and hand avatar. Use of the hand avatar as a "perceptual ruler" for objects in the scene may be different for richer environments, especially for those comprising objects with strong connotations of their size (e.g., a soda can). Finally, the degree of stereopsis, presence, and immersion and symptoms of cybersickness were not recorded, and therefore, the influence of these factors on individual participant behavior is unknown.

5 CONCLUDING REMARKS

The results of our studies together suggest that spatiotemporal coordination of reach-to-grasp in a high-fidelity immersive hf-VE is robust to the type of modality (e.g., visual/auditory) used as a sensory substitute for the absence of haptic feedback and to the size of the avatar that represents the fingertips. Avatar size may modify the magnitude of peak aperture in hf-VE when using spheres to represent the fingertips, but this change did not affect spatiotemporal coordination between reach and grasp components of the movement. We suggest that the modulation of aperture associated with avatar size may be rooted in the use of the avatar as a "perceptual ruler" for intrinsic properties of virtual objects. These results have implications for commercial and clinical use of hf-VE and should be evaluated in relation to technological limitations of the VR system (i.e., tracking accuracy, update rate, and display latency) (Stanney, 2002). Specifically, when VR is used for manual skill training or neurorehabilitation (Adamovich et al., 2005; Adamovich et al., 2009; Massetti et al., 2018), future work should consider the implications of avatar size on the transfer of learning from the VE to the real world especially in populations with deficits in multisensory integration.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. Please contact the corresponding author by e-mail.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Institutional Review Board (IRB) at Northeastern University. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MF, MM, MY, and ET conceived and designed research; MF and AS performed experiments; MF, MM, KL, AS, and MY analyzed data; MF, MM, KL, MY, and ET interpreted results of experiments; MF prepared figures; MF, MY, and ET drafted manuscript; MF, MM, KL, AS, MY, and ET edited and revised manuscript; MF, MM, KL, AS, MY, and ET approved the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.648529/full#supplementary-material

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