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Design and Evaluation of an Exergaming System for Children With Autism Spectrum Disorder: The Children's and Families' Perspective

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Children with autism spectrum disorder (ASD) have lower levels of physical activity than their typically developing peers. Barriers to participation include deficits in motor function and in social interaction, both of which reduce opportunities to engage in leisure activities that incorporate physical exertion. Because children with ASD also have higher than average levels of media use, exergames—video games that require bodily interaction to play—are a promising form of exercise. While studies have examined exergaming interventions for children with ASD, to date there has been little research on exergames that have been specifically designed for children with neurodevelopmental disorders, or qualitative analysis of players' and families' experience with exergaming programs. In this paper we present *Liberi*, an exergaming system involving kinaesthetic interaction within a virtual world, and designed explicitly for children with neurodevelopmental disorders. We report the results of a 6-week study where *Liberi* was played from the home by five children with ASD. The paper describes those aspects of the design that were successful and unsuccessful; how children and parents viewed the exergames; how the games were incorporated into the children's lives; and how parents envisaged exergames could be best deployed for children with ASD.

Keywords: game design, autism spectrum disorder (ASD), exergame, kinaesthetic interaction, active game

1 INTRODUCTION

Autism spectrum disorder (ASD) is one of the most common childhood onset neurodevelopmental disorders, with an estimated prevalence among North American children of 1 in 66 (Ofner et al., 2018) to 1 in 54 (Maenner et al., 2020). Four times more common in boys than girls (Ofner et al., 2018; Maenner et al., 2020), ASD is characterized by impaired social communication and interaction and restricted, repetitive interests and/or behaviours (American Psychiatric Association, 2013). A less recognized area of concern for children with ASD is physical inactivity (Srinivasan et al., 2014; Jones et al., 2017), which has been associated with poorer cardio-metabolic indicators and increased adiposity (Srinivasan et al., 2014), impaired psychosocial well-being (Hinkley et al., 2014), and lower cognitive functioning (Carson et al., 2016) in childhood. Children with ASD may face numerous barriers to engaging in physical activity (Fournier et al., 2010; Srinivasan et al., 2014; Must et al., 2015), including but not limited to deficits in motor coordination (Fournier et al., 2010; Must et al., 2015). As a result, they tend to be less physically fit (Tyler et al., 2014; Pan et al., 2016) and have higher rates of unhealthy weight (Broder-Fingert et al., 2014; Hill et al., 2015) than their typically developing peers. A 2017 review highlighted the critical need for interventions to support healthy levels of physical activity in children with ASD (Jones et al., 2017).

Exergames are "digital games that require bodily movements to play, stimulating an active gaming experience to function as a form of physical activity" (Benzing and Schmidt, 2018). Exergames are based on bodily interaction (Mueller et al., 2020). Players are immersed in a virtual world through kinaesthetic interaction, where the child controls their avatar through engagement of their muscles and lungs. On average, children with ASD spend more time playing video games than their typically developing peers (Mazurek and Wenstrup, 2013), which makes exergaming a particularly promising form of physical activity for this population. In a review of ten studies, Fang et al. (2019) concluded that when children with ASD engage in exergaming, it can lead to improvements not only in their physical fitness, but also in executive function and self-perception.

Most trials of exergames aiming to increase physical activity in children with ASD have used off-the-shelf games rather than ones designed specifically for persons with ASD (Fang et al., 2019), leading Benzing and Schmidt (2018) to recommend that to fully exploit the potential of exergaming, games should be customized to meet the needs of specific populations. Moreover, the research community has paid little attention to documenting the experiences of players and their families, how children perceive and interact with the exergaming system, and how exergame play is seated in the context of the children's lives. This knowledge is crucial to understanding the long-term success of exergames for children with ASD, and how exergames should be designed for this population.

To address these gaps in the literature, we piloted a 6-week in-home exergaming program among five children with ASD. They played the *Liberi* exergames (Hernandez et al., 2013), which were designed specifically for the needs of children with neurodevelopmental disorders and had been previously trialed with children with cerebral palsy (CP) (Knights et al., 2016) and children with fetal alcohol spectrum disorder (FASD) (Schneider et al., 2020). During the program, we tracked the children's play and level of physical exertion. Following the intervention, we conducted a focus group with the children and their parents to elicit their views and experiences of the exergames and the program.

In this paper, we present the results of this study. Findings include that *Liberi*'s in-game reward system was highly motivational, and participants focused heavily on identifying the most efficient way of gathering in-game coins. The children enjoyed playing with others; however, despite being verbal themselves, most preferred non-verbal communication. While children highlighted the importance of the game as a safe space, parents noted that the game had fostered confidence in the children, and had in some cases led to increased physical activity outside of the exergames. In all, five themes were developed relating to children's and families' perceptions of the use of the games over 6 weeks.

The paper is structured as follows. We first review related work on exergaming for children with ASD and what is known about game design for persons with ASD. We then present the *Liberi* exergames and explain how they are designed explicitly for children with neurodevelopmental disorders. We then describe our study, followed by an inductive thematic analysis of the focus group results. We conclude with discussion and lessons learned that apply to the design of exergames and exergaming programs for children with ASD.

2 RELATED WORK

In this section, we review the importance of physical activity for children with ASD, summarize prior experience in exergaming for children with ASD, and review prior work in the design of games for this population.

2.1 Physical Activity for Children With Autism Spectrum Disorder

As described above, physical inactivity is an area of concern for children with ASD (Fournier et al., 2010; Srinivasan et al., 2014; Jones et al., 2017; Benzing and Schmidt, 2018), as it has been associated with poorer cardio-metabolic indicators and increased adiposity (Srinivasan et al., 2014), impaired psychosocial well-being (Hinkley et al., 2014) and lower cognitive functioning (Carson et al., 2016) in childhood.

Children with ASD may face numerous barriers to engaging in physical activity, including but not limited to deficits in motor function (Fournier et al., 2010; Must et al., 2015) and self esteem, and social exclusion (McConachie et al., 2018). As a consequence, children with ASD have on average lower cardiovascular fitness (Tyler et al., 2014; Pan et al., 2016) and higher rates of unhealthy weight than their typically developing peers (Broder-Fingert et al., 2014; Hill et al., 2015).

Physical activity has been shown to bring benefits to children with ASD beyond improvements in cardiovascular fitness. Brief jogging sessions have been shown to produce transient decreases in subsequent levels of self-stimulatory behaviours and increases in appropriate play and academic responding (Kern et al., 1982). Exercise interventions have led to behavioural and academic improvements (Srinivasan et al., 2014).

2.2 Exergaming for Children With Autism Spectrum Disorder

Exergames are video games that combine the play of video games with physical activity (Yim and Graham, 2007). Some games have been designed primarily for entertainment but incorporate an exercise component. These include dancing games such as *Dance Revolution* (DDR) (Konami, 1998) and the *Just Dance* series Ubisoft (2009–2022), action games such as *Kinect Adventures*

(Microsoft Game Studios, 2010), and sports-themed games such as *Wii Sports* (Nintendo, 2006).

Many games that have been used in studies as exergames were not necessarily designed for promoting physical activity but rather to provide a novel form of immersive interaction based on bodily movement (Marshall et al., 2016). *Just Dance* integrates physical dance into a game, while the augmented climbing wall provides a digital experience based on the physical exertion of rock climbing (Kajastila et al., 2016). In these games, improvements in physical fitness may occur, but from the designers' perspective they are incidental to the kinaesthetic experience fostered by the play. Other exergames have been designed, however, with improvement of physical fitness as a primary goal, such as *Wii Fit* (Nintendo, 2007) and the cycling training game *Zwift* (Zwift inc, 2014).

Evaluation of the efficacy of exergames in the general population has been cautiously positive. For example, a meta-analysis of energy expenditure in the play of a variety of exergames, including *Wii Sports* and *DDR*, found significant increases in heart rate and energy expenditure over resting, with effect sizes similar to traditional physical activities (Peng et al., 2011). Positive benefits have been seen in emotions, attitudes and motivations toward physical activity (Goodyear et al., 2021), raising the potential of exergames to serve as a gateway to other forms of activity. A recent scoping review concludes, however, that evaluations of exergaming are highly sensitive to study design and game design (Marshall and Linehan, 2021). Minor design changes have been shown, for example, to more than double the time spent by participants in their target heart rate zone (Ketcheson et al., 2015). This led Benzing and Schmidt (2018) to conclude that "further developments such as customized exergames are needed".

As with virtually all other forms of exercise intervention (van Sluijs et al., 2007), exergame use can suffer from declining interest over time. For example, a study of 73 previously inactive, typically developing children showed initially high intrinsic motivation to use an exergaming system, which disappeared by week seven of the study (Rhodes et al., 2019). This decline in interest was accompanied by a decline in usage of approximately 40%. A study of exergame play by 70 children over 6 weeks showed that adherence to the program was predicted by the children's sense of social belonging (Kaos et al., 2019), implying that to be successful, exergames should foster social interaction.

Stronger benefits have been seen in exergames for children with neurodevelopmental disorders. For example, the *Liberi* exergames used in this study have been shown to improve cardiovascular fitness (Knights et al., 2016), experience of pain post-surgery (Cardenas et al., 2021), and social connection (Hernandez et al., 2014) in children with CP. In a 10-week study, children with CP played more minutes in the final week than in the first week (Knights et al., 2016). A 10-week in-school study involving children with FASD led to strong engagement throughout the 10 weeks (Schneider et al., 2020), and eventual improvement in executive function (Keiver et al., 2019).

A systematic review of ten studies of exergaming by children with ASD showed increases in moderate to vigorous physical activity and improvements in a wide range of measures including physical fitness, executive function, and self-perception, and reduction of repetitive behaviours (Fang et al., 2019). The games studied were off-the-shelf games including *DDR*, *Wii Fit*, and *Wii Sports*. Studies focusing on energy expenditure have shown time spent in moderate to vigorous activity ranged from 25.9% for Wii Sports through to 76.4% for *DDR* (Getchell et al., 2012), 76% in two Kinect-based games (Golden and Getchell, 2017), and 73–80% for the bespoke *Astrojumper* game (Finkelstein et al., 2013) when played by children with ASD.

Numerous studies have shown improvements through exergame play in symptoms and behaviours associated with ASD. Play of *DDR* and a cycling-based game led to decreases in repetitive behaviours and improvements in cognitive function (Anderson-Hanley et al., 2011); play of *Makoto Exergame Arena Training* led to improvements in response speed, executive function, and motor skills (Hilton et al., 2014), and play of *Wii Sports* led to improvements in social skills required for sport participation (Ferguson et al., 2012). Play of Kinect games led to improvement in perceived motor control skill, which may help as a gateway to participation in other forms of physical activity (Edwards et al., 2017). The *FroggyBobby* full-body movement game has been shown to improve aimed limb movements for children with ASD and developmental coordination disorder (Caro et al., 2017a).

There has been little study of the context in which exergames are deployed. Most studies of children with ASD focus on the play of the games in a controlled setting such as a research lab or clinic, which does not permit data collection around context of use. The design of the *FroggyBobby* exergame (Caro et al., 2017b) involved extensive interviews with physiotherapists, teachers, and children. The context obtained from these interviews informed the design of several iterations of the game, but was not the focus of the paper. More generally, context in the play of serious games has been addressed earlier by Richards et al. (2014). This paper suggested several ways in which context should impact game design. The most relevant of these to our work is that all stakeholders should be consulted to understand requirements, not just the end user. This motivates our contribution of interviewing parents to understand how play of exergames fits into the children's lives.

2.3 Designing Games for Children With Autism Spectrum Disorder

While the previous section established that play of exergames can bring benefits to children with ASD, we have also seen that the success of exergames is sensitive to their design and deployment, and that most cardiovascular fitness exergames that have been tested with children with ASD were not specifically designed for that population. Some children with ASD can successfully play commercial exergames (Fang et al., 2019), but because ASD is a spectrum, many children may experience difficulties, arising for example, from failure to account for deficits in motor function or in executive function. This raises the question of how exergames should be designed to best support children with ASD.

Many non-exercise games have, however, been designed for children with ASD. These are mainly therapeutic games intended, for example, to improve the player's ability to recognize faces (Tanaka et al., 2010), facial expressions (Alves et al., 2013), and emotions (Piper et al., 2006; Harrold et al., 2012; Bhatt et al., 2014; Sturm et al., 2016; Fridenson-Hayo et al., 2017), improve skills for social interaction and collaboration (Battocchi et al., 2009; Gotsis et al., 2010; Yan, 2011; Silva et al., 2014; Bhattacharya et al., 2015; Boyd et al., 2015; Bono et al., 2016; Winoto et al., 2016), reduce anxiety (Wijnhoven et al., 2015) and improve general practical skills such as navigating the bus system (Bernardes et al., 2015), improving vocabulary (Khowaja and Salim, 2019), and learning leisure skills (Blum-Dimaya et al., 2010).

From these and other games, a number of design guidelines have been proposed. For example, Whyte et al. (2015) argue the importance of an immersive storyline, the provision of rewards and feedback about goal progress, providing individualized training, and providing choice. They also stress the importance of minimizing frustration and negative feedback. Providing opportunities to play in groups can help with practicing communication and social skills.

Similar themes are reflected in the works of other authors, and from these, we distill the following areas that designers of games for children with ASD should consider.

2.3.1 Frustration and Behaviour Management

Children with ASD may have deficits in executive functioning which can impact their ability to process information and regulate behaviours. Examples include difficulties in planning, set shifting (ability to shift mindset to new concepts), response inhibition (ability to inhibit a dominant response), and working memory (temporarily storing and manipulating information) (Hill, 2004). Many video games require players to repeatedly fail at a task until finally succeeding, and deficits in executive function can lead to difficulty in processing such frustrating events (Schneider et al., 2020). Games should therefore embed behaviour management strategies (Alarcon-Licona et al., 2018) and designers should aim for "pleasant frustration" that provides challenge without excessive annoyance (Hiniker et al., 2013).

Two aspects of games can make frustration more tolerable: children with ASD appear to prefer rules that are enforced by a computer to potentially arbitrary rulings from a human (Piper et al., 2006), and failure may be more acceptable in a game context than in tasks arising in daily life (Durkin et al., 2013). Games should provide strong positive feedback when the player is successful and minimize negative feedback when they make a mistake (Sturm et al., 2016; Khowaja and Salim, 2019).

2.3.2 Choice

Researchers have found that children with ASD consider choice to be important in gameplay (Carter, 2001) and that designers should therefore allow children to play on "their own terms" (Christinaki et al., 2013).

2.3.3 Sensory Design

Some children with ASD process visual and audio information differently from their typically developing peers (Marco et al., 2011), and these differences should be recognized in game design. Extraneous sensory input should be avoided (Sturm et al., 2016; Khowaja and Salim, 2019), such as multiple simultaneous visual and auditory signals (Yan, 2011). Some children prefer the use of narrative voice over text (Harrold et al., 2012), while others prefer visual stimuli over audible (Yan, 2011). Haptic input (such as a vibrating controller) should be avoided, or at least optional (Ellis et al., 2021). Games should be simple and with low detail to avoid distraction (Christinaki et al., 2013).

2.3.4 Interaction Design

As some children with ASD have deficits in motor function (Fournier et al., 2010), games should avoid the need for fine-motor precision (Hiniker et al., 2013). Kinaesthetic experiences (involving bodily movement) may enhance engagement in games (Bhattacharya et al., 2015; Bossavit and Parsons, 2016).

2.3.5 Social Interaction

Games should be designed around social deficits associated with ASD; for example, Winoto et al. (2016) designed a game to teach joint attention skills that did not require players to look at each other. Involvement of teachers and scaffolding may be necessary to build toward more elaborate social interaction (Bhattacharya et al., 2015).

From this review of related work, we conclude that exergames show promise for promoting physical activity in children with ASD, particularly given this group's enjoyment of digital media (Mazurek et al., 2012) and receptiveness to kinaesthetic interaction in games (Bossavit and Parsons, 2016). Earlier experience with exergames for children with neurodevelopmental disorders suggests these games may have greater success with these populations than seen with typically developing children.

To date, however, little has been reported on exergames designed specifically for increasing cardiovascular activity in children with ASD, and there has been study of what aspects of exergames may be particularly appealing or difficult for children with ASD, or how the play of these games fits more generally into the lives of these children and their families. Our study with the *Liberi* exergames, described next, addresses these issues.

3 LIBERI EXERGAMES

The *Liberi* exergames are a collection of seven pedalling-based minigames featuring different styles of play (Hernandez et al., 2013). They are fast-paced and full of action, using a whimsical cartoon art style. The collection includes a lizard racing game, a zombie cat defence game, a space hockey game, a jellyfish brawling game, a roundup game where players lasso runaway sheep, an action game for being the first dinosaur to collect 10 eggs, and a platformer game featuring spiky balls in a desert ruin. The games are accessed via portals in a small village. Three of the games are collaborative, three are competitive, and one involves team-based competition. All games can be played solo, by

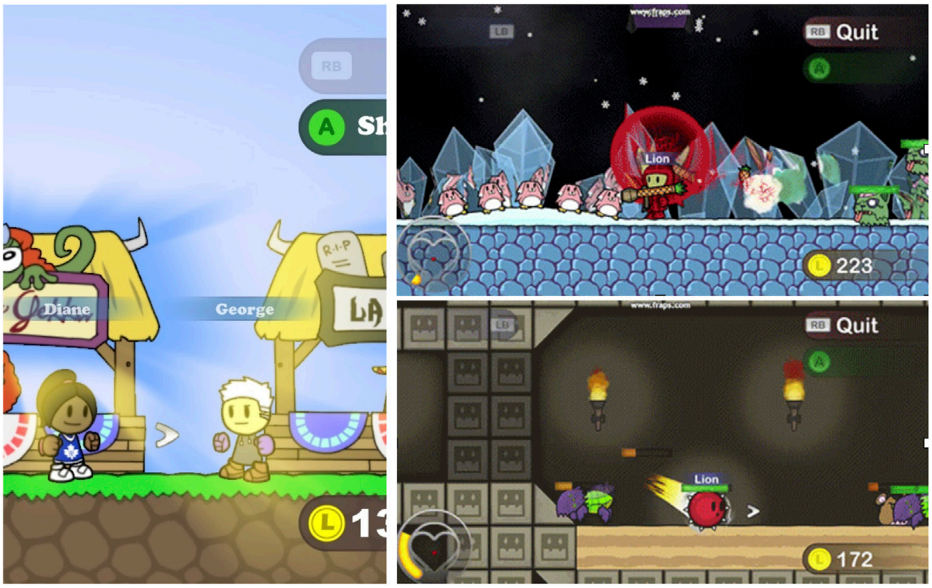

FIGURE 1 | Examples of the *Liberi* exergames. *Top-right:* Wiskin Defence: the player defends pink wiskins from attacking zombie cats using a pineapple gun; *Bottom-right:* Dozo Quest: the player traverses a maze as a spiky ball, encountering and defeating enemies. *Left:* two players meet in the village where they can chat and go shopping.

FIGURE 2 | Child playing *Liberi*. The child pedals to move their avatar in the game and uses a standard game controller to specify movement direction and perform actions.

allowing AI-controlled "bots" to stand in for other players. **Figure 1** shows examples of the games.

Players pedal a stationary recumbent bicycle to control their in-game characters (avatars). The faster the player pedals, the faster their avatar moves. Players use a standard game controller; the controller's left stick is used to steer the avatar and aim, and a button is used to perform game actions such as jumping or shooting. **Figure 2** shows a child playing the games.

The *Liberi* exergames were originally developed for children with CP. The recumbent bicycle is custom designed to provide support for persons with gross motor deficits (Hernandez et al., 2012). The mapping of pedaling speed to in-game speed is personalized to match the game's difficulty to the player's physical abilities (MacIntosh et al., 2017). The gaming controls are simple, limited to a single joystick and a single face button; this means that the games allow only one action at a given time, and use context to determine what action is most appropriate (Hernandez et al., 2013).

Liberi has been trialled among children with CP in both the home environment (Knights et al., 2016) and clinical setting (Hwang et al., 2017), with children with FASD in an elementary school (Schneider et al., 2020), and at home for typically developing children (Kaos et al., 2018). In the following sections, we describe some of the design features that make the *Liberi* exergames particularly suited to children with neurodevelopmental disorders.

3.1 Games for Exercise: Action and Simplicity

Liberi's minigames involve fast action to encourage players to engage in vigorous physical movement. For example, in *Gekku Race*, players take the form of a "Gekku" lizard and race against other players to the top of a wall. They can spit cashews up the wall at the other players to slow them down. The primary mechanics in the game are pedalling to move quickly up the wall, using a joystick to aim at other players, and pressing a face button to fire a cashew. In the game *Wiskin Defence*, players pedal furiously to charge up a weapon, which they then use to attack and destroy various kinds of zombie cats before they can reach the rabbit-like "Wiskin" characters (**Figure 1**). In *Dino Dash*, players control a scurrying dinosaur that must grab eggs and return them to a nest for hatching, while dodging the “shouts” of enemy dinosaurs that will lead them to drop their egg.

The games are intentionally simple, as it may be difficult for players to engage in complex strategy or immersive storytelling while physically moving and out of breath. This is particularly true of children with motor deficits, for whom carrying out basic pedalling movements may be cognitively demanding (Hernandez et al., 2013).

3.2 Supporting Group Play

While the *Liberi* games can be played solo, they are also designed for group play (Hernandez et al., 2014), which can be cooperative, competitive or team-based. Small groups of players inhabit the same game world and can communicate verbally via a headset connected to a voice-over-IP call, or non-verbally by interacting with others’ avatars. Players may choose to join mini-games together. The games are accessed as portals in a small village. To enter a game, players stand on its portal together and press a face button. When the game finishes, the players are returned to the portal. The village is small so that players can find each other quickly. All players are automatically placed in a voice chat together, allowing them to negotiate which game to play next.

Minigames involve short bursts of activity (1 to 2 minutes), making it easy for newly-arrived players to join a group, possibly moving between different types of play depending on peoples’ interests and abilities. Willingness to accommodate others’ interests and abilities was observed in an exergaming study involving children with CP (Hernandez et al., 2014). In a school-based trial that recruited children with FASD, participants were observed leveraging the open-world nature of the game to invent new games that they could play together, such as tag (Schneider et al., 2020). In competitive games, these same children collaborated together against the computer-controlled “bot” players, showing that they valued the social aspect of play more highly than the desire to win as individuals.

The ability to play together was shown to be a key factor in motivating children with CP (Knights et al., 2016) and FASD (Schneider et al., 2020) to continue to engage with the *Liberi* exergames over periods as long as 10 weeks.

3.3 Long-Term Objectives for Long-Term Motivation

Participants’ interest in exercise interventions in general (van Sluijs et al., 2007) and in exergaming in specific (Rhodes et al., 2019) tends to wane over time. *Liberi* has several features that were designed to sustain players’ interest over weeks or months: players earn in-game currency, which they can then spend at in-game stores (**Figure 1**). For example, players are awarded coins every time they defeat a zombie in *Wiskin Defence* or return an escaped sheep to the ranch in *Bobo Ranch*. These coins can be used at a variety of shops to purchase costumes, allowing players to customize their avatars. Players can also purchase amusing weapons for use in the *Wiskin Defence* game, such as the fish-shaped “Cod of War” or the “gnomigun” that shoots exploding garden gnomes.

The items available range from those that are affordable within a single play session to “deluxe” goods whose purchase price requires players to engage in several gaming sessions to accumulate the required coins. An earlier study found that children with FASD showed broad interest in shopping, in saving up for items, and in simply collecting coins without specific interest in spending them (Schneider et al., 2020).

3.4 Design Considerations for Autism Spectrum Disorder

As described earlier, the *Liberi* exergames were originally designed for play by youth with CP (Hernandez et al., 2014) and have since been trialled among children with FASD (Schneider et al., 2020) and typically developing children (Kaos et al., 2018). Elements of the game’s design addressing the characteristics of children with other neurodevelopmental disorders are also applicable to ASD.

3.4.1 Designing for Deficits in Motor Control

Children with ASD have on average poorer fine and gross motor skills than their typically developing peers (Fournier et al., 2010). Based on its origins as a game for children with CP, *Liberi* provides support for play by children with motor deficits. The game is played with a standard game controller, but the use of the controller is simplified to account for possible deficits in fine motor control. A left analogue stick is used to aim and select the avatars’ direction of movement. The games require only one button for actions (jump, dash, shout, etc.), with the appropriate action automatically selected based on the context. The interpretation of pedalling speed from the bicycle adjusts for differences in gross motor ability: input is smoothed to account for uneven pedalling (Hernandez et al., 2012) and the mapping from pedalling speed to in-game speed is personalized to the player’s abilities (MacIntosh et al., 2017).

3.4.2 Designing for Deficits in Executive Function

ASD is associated with impairments in executive function, including effects on mental flexibility, planning, working memory, and response inhibition (Robinson et al., 2009). Each of these areas could impact game play experience, and the *Liberi* exergames are designed to mitigate possible deficits in these areas.

One goal in *Liberi*’s design is to limit the impact of failure. For example, in the *Dozo Quest* minigame (**Figure 1**), players may fall off a platform, requiring them to repeat part of a level. In many platformer games, falling off a level may require players to repeat a large segment of the level. In contrast, *Dozo Quest* is designed so that falling from a platform has a visible effect, but requires little repetition. This may reduce frustration when experiencing the failure that is a core aspect of gameplay.

Another design goal is to limit the load on working memory. Again using the *Dozo Quest* minigame as an example, players navigate a maze. Mazes usually require working memory to keep track of branches already tried. In *Dozo Quest*, all paths in a maze eventually lead to the same place. This reduces players’ need to remember and visualize the structure of the maze, mitigating potential frustration from getting lost. In the *Bobo Ranch* minigame, players are required to remember the positions of sheep and other players that may not always be on screen. To reduce the need to precisely recall these positions, markers are used to show the directions of other players and sheep.

3.4.3 Designing for Barriers to Participation

Must et al. (2015) have listed barriers to participation in physical activity among children with ASD. These include the need for supervision, the potential lack of friends to play with, and social exclusion by their peers. *Liberi*'s online gameplay has the potential to reduce these barriers through the use of avatars to represent players and the structured form of the activity. The representation of players via avatars may reduce barriers to engaging in group play, such as impairments in social pragmatics or difficulty in understanding facial expressions. The core focus on gameplay in interaction with others might aid with social issues identified by Williams White et al. (2007), such as a tendency to dwell on certain topics or difficulty understanding emotions.

3.4.4 Addressing Guidelines for Games for Children With Autism Spectrum Disorder

These features of *Liberi* address the five design recommendations that we have drawn from prior literature. Explicit design decisions were made to *reduce frustration* (**Section 2.3.1**), such as limiting impact of failure as described above. Addressing the guideline to *offer choice* (**Section 2.3.2**), players are offered the choice of several minigames, and the ability to customize their avatar's appearance. Counter to advice around *sensory design* (**Section 2.3.3**), the games feature multiple, simultaneous visual and auditory signals through sound effects and particle effects, but do provide the kinaesthetic interaction that is valued by Bossavit and Parsons (2016). Following *interaction design* guidelines (**Section 2.3.4**), the games accommodate deficits in fine and gross motor control. Finally, *social interaction* (**Section 2.3.5**) is a core feature of the games, and following the advice of Winoto et al. (2016), are mediated through the use of avatars.

Thus, we see that *Liberi*'s design matches needs arising from characteristics of ASD. To determine how effectively the *Liberi* exergames work with a population of children with ASD, we carried out a 6-week in-home pilot study involving five children with ASD. As reported in **Sections 5 and 6**, this study allows us to draw conclusions about the strengths and weaknesses of *Liberi* from the perspectives of both the children and their families.

4 METHODS

As described below, the study consisted of a pre-program meeting for information dissemination and initial questionnaires, a 6-week in-home exergaming program, and a post-program focus group for parents and children. This study was carried out under the aegis of the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board. Completed a combined letter of information/consent form describing the study protocol, and children signed an assent form describing the study in simplified form.

4.1 Sample and Setting

A convenience sample of five children with ASD and one parent per household were recruited through the KidsInclusive Centre for Child and Youth Development in Kingston, Ontario. Children were required to be between 8 and 12 years of age (the age group targeted by the game developers), verbal, able to complete age-appropriate questionnaires (as determined by the parent), physically inactive (scored 1-3 on the child-completed Physical Activity Questionnaire for Children (PAQC) (Kowalski et al., 2004)), and able to take part in physical activity (as per the parent-completed Physical Activity Readiness Questionnaire for Everyone (PARQ-E) (Warburton et al., 2015)). Households required a high-speed internet connection and space for a recumbent bicycle. The bicycles were delivered to participants' homes and two research assistants set up the gaming stations and provided individualized training on how to connect to *Liberi*, use the headphones to communicate with other players, and attach the arm-mounted heart rate monitor.

4.2 Pre-Program "Meet and Greet"

The participants included five boys (two aged eight and three aged 10 years) and their mothers. Participants attended a 2-h meeting 1 week prior to the start of the program. The purpose was to explain the study procedures, to demonstrate the exergames, and to allow the children an opportunity to play them. Parents completed two questionnaires: the Behavior Rating Inventory of Executive Function, Second Edition (BRIEF2) (Gioia et al., 2015) and the Social Responsiveness Scale, Second Edition (SRS-2) (Constantino et al., 2003). Scores on the BRIEF2 indicated potentially clinically elevated to clinically elevated impairment in executive functioning. The SRS-2 scores for all five children indicate deficiencies in reciprocal social behaviours that are clinically significant, ranging from mild to moderate to severe interference with everyday social interaction.

As a baseline fitness assessment, the Maximal Multistage 20 m Shuttle Run Test (Leger et al., 1988) was performed and the maximum heart rate recorded in this test was used to define the child's target heart rate during gameplay. Moderate-to-vigorous physical activity was defined as 64% or more of this observed maximum heart rate (Verschuren et al., 2011).

Garmin Vivofit Jr. wristband activity trackers were provided to the children, who were asked to wear them 24 h a day for the study duration. The trackers were connected to parents' phones and the data were accessible to the research team online. Participants were additionally asked to wear the activity tracker for 2 weeks prior to the start of the study to establish a baseline.

4.3 The Exergaming Program

During the 6-week program, the *Liberi* server was opened on 4 days each week for a 90-min play session (the days and times were chosen in consultation with the families). Children were asked to play the games three times per week for at least 45 min each session. A research assistant at Queen's University remotely monitored players' activity to ensure that there was no bullying or inappropriate language when players communicated with one another and was also available to

TABLE 1 | Minutes played by participant and week. In week 4, participant C2 was on vacation; in week 6, participant C4 was on vacation.

Player	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Total
C1	19.6	23.0	92.9	76.8	114.8	94.2	421.2
C2	76.3	133.6	0.0	–	97.3	34.9	342.1
C3	117.8	87.2	36.9	75.0	56.8	42.6	416.1
C4	68.8	98.2	0.0	37.4	44.6	–	248.9
C5	0.0	56.2	0.0	0.0	0.0	0.0	56.2
Total Minutes Played	**282.4**	**398.1**	**129.8**	**189.1**	**313.5**	**171.7**	**1,484.6**

TABLE 2 | Percentage of play time at or above target heart rate by participant and week. Data for participant C5 is not shown, as they had only minimal participation in the study (see **Table 1**).

Player	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
C1	94.3	10.3	65.2	39.8	70.9	53.5
C2	63.2	70.2	0.0	–	94.1	99.6
C3	0.0	12.5	25.4	6.8	23.3	11.2
C4	98.6	100.0	0.0	38.8	0.3	–

provide technical support over the telephone. Another research assistant contacted families by telephone weekly to ascertain whether families were experiencing any unreported issues with the games or the program.

4.4 Post-Program Focus Group

Four families (eight participants) attended a focus group at the conclusion of the 6-week program. An experienced focus group facilitator, who was not part of the original research team and had no vested interest in the findings, led the focus group using a semi-structured interview guide developed by the researchers. The questions were designed to obtain feedback on what children and parents liked and disliked about the exergaming program and the study procedures, and whether children's engagement in exergaming could be sustained in order to provide a viable exercise intervention over the long term. The discussion was audio recorded and transcribed.

A transcript of the focus group was analyzed using reflexive thematic analysis (Braun and Clarke, 2012; Braun and Clarke, 2019). Themes were developed inductively, with a semantic and realist perspective. The transcript was independently reviewed by the focus group facilitator and two members of the research team to develop a list of initial codes using NVivo 12 Plus (QSR International Pty Ltd., 2018). The three analysts met to discuss and create a consensus codebook. The transcripts were then recoded and each analyst independently developed themes. Another meeting was held to discuss and reach consensus on the final themes that best captured important topics/issues identified by the participants.

5 RESULTS: PARTICIPATION AND ENERGY EXPENDITURE

Table 1 shows participants' play time over the 6 weeks of the study. Participants are labeled as C1 through C5 to preserve their anonymity. Participants played an average of 49 min per week. Four participants engaged with the game regularly, while one (C5) played in only 1 week. On average, game sessions lasted 37 min, with players engaging in on average 1.3 sessions per week. For participants who engaged in little physical activity prior to the study (as indicated by low PAQ-C scores), this represented a notable increase.

Table 2 shows the participants' energy expenditure while playing. Our goal was that participants reach a moderate to vigorous level of physical activity (MVPA). Over all time played, players achieved this level of activity 58.2% of the time. Note that this table does not include data for participant C5 who, as shown in **Table 1**, participated in only 1 week of the study.

Table 3 shows the participants' step counts as measured by the Garmin Vivofit Jr. step tracker. Participants were asked to wear the step trackers for 2 weeks prior to the start of the program and over the 6 weeks of the program. Weeks without values indicate that a participant preferred not to wear the device during that week. Because these step counters do not track cycling motions, the step counts represent physical activity outside the exergame.

This data shows that in general, step counts during the intervention remained steady or increased over the two baseline weeks. This suggests that playing the *Liberi* games did not displace other physical activities the child may have been engaging in prior to the program. The baseline step counts shown in **Table 3** are considerably below the average daily step count for boys of 12,853 reported by Johnson et al. (2010).

5.1 Player Experience

At the end of the 6-week program, players completed the Self-reported Experiences of Activity Settings (SEAS) questionnaire (King et al., 2014). The SEAS is a validated scale designed for

TABLE 3 | Weekly steps measured by the Garmin Vivofit Jr. activity tracker. The children were asked to wear the tracker for the 2 weeks prior to start of the study, and the 6 weeks of the study.

Player	Pre-program week 2	Pre-program week 1	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
C1	4,876	5,465	5,218	4,736	4,617	4,425	–	–
C2	3,531	3,989	3,801	1,106	7,907	5,048	4,181	2,109
C3	891	281	447	–	–	1,042	803	1,061
C4	4,932	6,593	7,356	6,469	8,349	9,182	10,773	10,566
C5	892	2,935	2,670	4,149	2,147	8,180	5,623	2,471

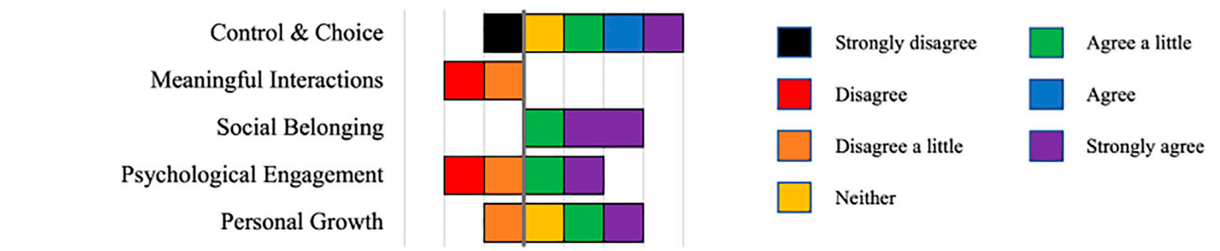

FIGURE 3 | Participants' responses to Self-reported Experiences of Activity Settings scale. Data for participant C5 is not included, as they had minimal participation in the study (see **Table 1**).

children with neurodevelopmental disorders to capture their perception of recreation and leisure activities. The questions avoid lengthy text and allow participants to point to pictographs to select points on a Likert scale.

The results are shown in **Figure 3**, in the form of a stacked diverging bar chart (Heiberger and Robbins, 2014). The results should be interpreted in the context of the small number of responses; for example, only two participants provided answers on the *Meaningful Interactions* scale.

Under *Control and Choice*, participants' responses varied from "Strongly Disagree" to "Strongly Agree". Participants were largely negative about the game's provision of *Meaningful Interactions*, yet were very positive about the game's provision of *Social Belonging*. Responses were mixed under *Psychological Engagement* and *Personal Growth*.

6 RESULTS: THEMATIC ANALYSIS

Five overarching themes, comprising 18 subthemes, were developed. These themes include motivation, program benefits, frustration, long-term adherence, and activity tracker. To ensure confidentiality, quotations are labelled with 'C' and a unique number to identify children, or 'P' and a unique number to identify parents.

6.1 Theme 1: Motivation

The children discussed several factors that motivated them to play the exergames. These included earning money and shopping in the e-store, winning, playing with others, and having fun.

Subtheme 1.1: Earning Money and Shopping in the e-Store

Earning and spending money on in-game purchases, including additional costumes and accessories for players' avatars, was one of the primary factors motivating play. Accordingly, when asked to rank the mini-games in order of preference, games that were recognized by participants as "good for money" (C4) were rated the highest. One participant (C1) even suggested that the exergaming program should award money simply for pedalling, as opposed to requiring extensive mini-game play. Participants also described saving up their money to afford expensive e-store items: "I usually just save up the money and then get the thing I like the most in the stores." (C2)

Subtheme 1.2: Winning

In addition to earning money, participants were motivated by the competition inherent in the mini-games. The likelihood of winning was mentioned as a primary factor contributing to game enjoyment. As one participant stated: "I liked Gekku Race. It was just my favourite. I like racing little bots because I always won." (C2)

Subtheme 1.3: Playing With Others

The children also enjoyed having the opportunity to play with others. Three of them (C1, C2, C4) often followed each other's avatars around the island and engaged in mini-games together, which increased their enjoyment: "I liked it because I usually found [C1] playing and I like playing with the other people." (C2) For this reason, two participants suggested game modifications that would increase the ease of this interaction: "Actually, I think that there should be a mini-maps system that shows you where the other players are or what games they are in, you know? So that you can play together more." (C2) "There should be this thing which has coloured arrows showing you where other people are going." (C1)

Through the use of headsets, players had the opportunity to communicate with one another. Nevertheless, only one (C2) stated that he would have liked to talk with others (however, technical difficulties prevented this). Another participant reported that he preferred to simply socialize through in-game virtual interactions: "I had [the headset] on but I didn't want to talk." (C1)

Subtheme 1.4: Having Fun

Having fun was also mentioned as a primary factor motivating participants to engage in the exergames. Similarly, when asked why certain mini-games were not played extensively, one participant said "Eh, I just found them [other games] more fun." (C2)

6.2 Theme 2: Program Benefits

Participants described a variety of program benefits, including increased physical activity, more family socializing, the establishment of a safe space, and increased confidence.

Subtheme 2.1: Increased Physical Activity

Three parents (P1, P2, P4) expressed pleasure at seeing their children engaging in more physical activity than usual. As one parent described, "For me it's really just seeing him moving his body instead of sitting in front of the screen not moving his body." (P2) Furthermore, one parent reported that her child's teachers also noticed changes in fitness and activity levels at school: "Yeah, I know it definitely improved like, even when [C1] had to do the beep test again in gym, he actually went up, gym teacher was very impressed." (P1)

Subtheme 2.2: More Family Socializing

One parent also mentioned that the exergames encouraged her child to share more about his experience with the game as compared to other videogames. Consequently, the exergames prompted additional family time discussing the games: "Like, when they are first starting a videogame, it's kind of, they are in their zone. But this kind of brings them out, and they are like: 'Hey, I was trying to do this. . .'" (P1)

Subtheme 2.3: Establishment of a Safe Space

One parent described her appreciation that the *Liberi* platform provided a safe space for the children to play online videogames: "Yeah, I think it is a social aspect. It's like a safe zone for them, it's knowing there is gonna be no bullying, there is gonna be, you know, no judgment. Like a safe place to say how you are feeling." (P4)

Subtheme 2.4: Increased Confidence

Two parents (P1, P4) noticed a sense of increased confidence in their children, which they attributed to the exergaming program. One parent explained: "I am so impressed that he wants to do things outside of biking. Yeah, it's really opened up like the door for him, to do more, like, even doing this has improved his self-confidence in some kind of way because he wants to challenge himself." (P4)

This same participant (C4) had even joined the school cross country team since participating in the exergaming program. Another parent reported similar changes in her child at school: "[The gym teacher] has noticed a lot more movement, not as much sitting back, starting to see participation more." (P1)

6.3 Theme 3: Frustration

In order to understand factors that may limit participants' future enjoyment of and participation in the exergaming program, several focus group questions probed sources of frustration.

Subtheme 3.1: Technical Difficulties

Numerous technical difficulties, largely with respect to participants being unable to connect to the online platform, were experienced throughout the 6-week program. Although there was technical assistance available via phone, participants often had to wait several minutes in order for the staff member to remotely fix the issue; this delay often interfered with the participants' playing time. One parent described these frustrations as follows: "But just the glitches, like there were so many glitches that it was really frustrating for everybody. So it would be great if the systems were installed and that everybody had lots of chances to use them before the study. And if we really knew that it would work well before the study started."(P2)

Parents recounted that these technical difficulties often frustrated the participants and occasionally led to behaviour management issues: "When it first happened, you know, it's kind of like, like not a full-on meltdown, but 'why, why is this happening?' So I would kind of prep, if this is going to happen, there'd be like a reward system trying to distract him until he can get back on, and sometimes he would not get on until there is about 20 minutes left in the time. So, especially for some kids on the spectrum that can't self-regulate and fully grasp the whole situation. . ." (P4)

Suggestions for future technical support included an online support system: "I would like an online chat maybe for having tech issues because I know that a lot of parents were calling at the same time and the phones were busy. If there is maybe like an online screen." (P4)

Subtheme 3.2: Lack of Game Variety and Insufficient Difficulty

Three children (C1, C2, C4) also mentioned a desire to have a wider selection of games with respect to sophistication and difficulty levels. When asked about the difficulty level of some of the current mini-games, they used words such as 'easy' and 'boring', and expressed a desire for more 'sophisticated graphics' and more 'challenging games'.

Subtheme 3.3: Lack of Game Consistency

In order to maintain a degree of novelty, each week a different set of mini-games was available to play. This was a source of frustration for three participants (C2, C3, C4), as they would be excited to play a particular game, only to discover that it was not available that week. As one parent described: "When he fixates on one thing, the fact that it wasn't there the next time or the day after that, and you know that it was a little harder to get him to the other games, when he wanted to go on that game today." (P4)

Participants therefore suggested that all games be available at all times to allow for additional consistency and choice when engaging in the exergames: "I think it's a bit more fun when you can always have a little bit more [choice], you can pick and choose which game you want instead of having to wait till it's actually out there." (C2)

Subtheme 3.4: Perceived Unfair Play

Children expressed frustration with respect to the 'bots' (computer-controlled players) and perceived unfairness in their abilities. In some games, players (incorrectly) believed that bots were exclusively targeting them: "Whenever you got ahead of them, they just constantly targeted you and none of the other bots that were ahead of you, just you. And they did it until you were last and it was really frustrating."(C2)

Participants therefore had suggestions with respect to making the mini-games more 'fair'. For example: "You should make like a minute recharge [on bots being able to attack the player]. That'd make it more fair, like 1-min recharge." (C4) Interestingly, this frustration with perceived unfairness was only expressed with respect to the bots and not with respect to other players. In fact, participants indicated that the chance of losing to another other player added a sense of enjoyment: "I'd say Gekku Race because then you have somebody who is not a bot and they actually have a pretty decent chance of beating you." (C2)

Subtheme 3.5: Sensory Considerations

One parent expressed the need to account for the sensory sensitivities experienced by some children with ASD. Her child was unable to wear the activity tracker and also struggled to keep the heart rate monitor on due to a dislike for the sensory aspects. Additionally, she expressed a desire for a wider variety of games that would appeal to different levels of sensory stimulation: "I was wondering [. . .] for games to be just not so much competitive. He likes to have, whether it's drawing or colouring, or looking at pictures and colouring the pictures, to be more of a relaxing thing, even though he could still pedal and colour or something." (P3)

6.4 Theme 4: Long-Term Adherence

The focus group questions also aimed to elicit factors that may facilitate or hinder long-term adherence to exergaming.

Subtheme 4.1: Novelty Factor

Parents expressed concern over whether exergaming would continue to be motivating and enjoyable for the participants once the novelty factor had worn off. "I know for [C3] it was more, I think it was more the novelty, it was new or something. If maybe there were less glitches, because when you would be in the middle of the game and it would glitch and then he would not want to go back to it or he didn't want to play the next day [. . .] I don't know if it was working more, you know, whatever, if he didn't have problems, maybe he would enjoy it more but I know by the end of it, he was like: 'I am done, I am not playing this game anymore.'" (P3)

Nevertheless, one parent thought that even if her child was no longer self-motivated to play, he enjoyed the games enough that they could be implemented as mandatory daily physical activity that had to be completed prior to playing other videogames: "I'm guessing that something I would have to say you need to put half an hour on bike before you are allowed to use something else because I think he would go to the something else first. But then at least there's something I can have him do that he would enjoy." (P2)

Subtheme 4.2: Program Flexibility

All parents expressed a concern for the lack of flexibility in the exergaming program with respect to the rigid windows during which the online platform was available: "I would have liked if we could have had the option to choose whatever night we wanted to do as long as we got three nights a week or whatever. Because sometimes it was inconvenient to do it on the night that we had to do it and he was reluctant to whatever and it was a, you know, it was, there was less joy in it as you know." (P2)

Parents explained that this could easily be solved by having the platform open for a longer duration and on additional days during the week. When asked about long-term adherence, one parent described that perhaps the program could be seasonal: "For us, I would say in the winter time [we would participate], for sure, because in spring and summer and fall, you kind of want to get out and do more. Where we live, it's kind of limited, like there is no big pools like within the city, there's no walking in our town. So yeah, as a winter activity, that would be great." (P1)

Subtheme 4.3: School Implementation

Opinions were mixed on the idea of implementing exergaming in schools. One child (C1) expressed concern that other children would not be careful with the equipment, while another (C2) was concerned about the lack of a peaceful or safe environment in which he could play. Conversely, another participant stated that he would enjoy playing at school because: "At school you just go to one quiet room and you can be alone for as long as you need it for until the server shuts down. And then you can just relax after." (C4)

Parents were more uniformly supportive of the idea, and one parent had already broached the topic with her child's school: "I spoke to, because I work for the school board and stuff, so I spoke to the principals and stuff and said listen, if this ever happens to get into the schools, I said whether it be in a body break room or whatever, I said this program would be awesome for some of these kids on the spectrum or even off. You know what I mean?" (P1)

6.5 Theme 5: Activity Tracker

Although the activity trackers were meant to serve as passive activity monitors, they stimulated extensive discussion during the focus group.

Subtheme 5.1: Competing With Parents And/Or Self on Activity Tracker

Parents and children alike mentioned that the activity tracker played an important role in motivating physical activity, and two children (C2, C4) competed with their parents on daily step counts. "He loved the watch in the beginning and I liked that I could see him and the steps he was getting and we did kind of 'hey, hey, hey, hey, not enough steps today, let's go for a walk'. So it was motivating for us and we did compete." (P2) "Yeah because me and my mom compete and it's good to track your steps so you know which steps you took in a day. Then I compete with my mom so I'd win and then I brag to my mom." (C4)

One parent quantified the increase in physical activity (outside of the exergaming program) that was motivated by the activity tracker: "He went from doing like 2,000 steps and 1 day he came home and he had like 19,000 steps and like 'who is this kid?' because he is so obsessed looking at how many steps he has a day. So that was the biggest benefit we got from the program was the watch [activity tracker] for him." (P4)

Subtheme 5.2: Behaviour Support

In addition to tracking steps, the parents were also able to program specific tasks (e.g., chores) or behaviours into the tracker that would award their children points when completed, which was described as a benefit of the activity tracker: "We loved the watch [activity tracker] [. . .] We had it linked up with like, even like the smallest chores in the house, like feeding dogs, putting your shoes on the left to the right foot. . .the biggest motivating factor was the watch [activity tracker]." (P4)

One parent also mentioned the intention of having such a tracker implemented at school to assist with behaviour management: "At school it was fantastic too. Like so good that through the school OTs and support system we tried to reach out to see if they can put in for it because it was just so good." (P1)

Lastly, given the success observed with the activity tracker, one parent expressed a desire to link the points earned on the activity tracker with the exergaming e-store to further enhance motivation: "Did the coins that they earned on the, on our app [activity tracker app], like the app on my phone, translate into the game? No? That would have been motivating. That would have gotten him to do more chores." (P2)

7 DISCUSSION

This study shows that there is room for cautious optimism about the use of an exergaming system such as *Liberi* to encourage physical activity and social interaction in children with ASD. Four of the five children engaged with the exergames over most of the 6 weeks of the program (**Table 1**). Participation fell below the 45 min three times/week that we had asked the children to play. Participants performed on average, however, close to 1 hour of physical activity per week in the games, and step count information indicates that this was new activity, not displacing existing activity (**Table 3**).

The reported percentage of play time at the moderate to vigorous physical activity (MVPA) level (**Table 2**) falls in the mid-range of exergames analyzed by Getchell et al. (2012), but for considerably longer play sessions. The results compare favourably to activity levels for organized sports for typically developing children. For example, Sacheck et al. (2011) measured 33% of time spent at or above MVPA in 50-min soccer matches for boys and girls aged 7–10, while Guagliano et al. (2013) saw 30% time at MVPA in 60-min games of netball, basketball and soccer.

Participants described play as fun (**Section 6.1**), motivated by the game's coin collection and shopping mechanics, and play with others. Difficulties were also observed, such as frustration arising from technical issues and preferences for more complex and challenging games.

In this section, we consider issues around the design of the game and the context of its deployment. Families were enthusiastic about the games, citing examples of improved activity and confidence in their children, as well as social advantages within the family. We then consider how play of *Liberi* by children with ASD compares to play by children with other neurodevelopmental disorders.

7.1 Game Design

To date, *Liberi* is one of very few exergames designed specifically to increase physical activity in children with neurodevelopmental disorders, and this study represents the first experience of *Liberi* among children with ASD. The thematic analysis of **Section 6** showed that the primary factors motivating play were enjoyment of the games, earning money in the minigames, using the item stores, and playing with others.

Children were observed to optimize their play to accrue coins as efficiently as possible, choosing the games where coins could be obtained more quickly. This implies that the mechanic of earning and saving coins for later reward provided a powerful incentive to play and that children were willing to save up over several play sessions for expensive items.

Some game situations led to frustration in the children. Players found the behaviour of AI-controlled enemies ("bots") to be unfair. The bots were not, in fact, programmed to target specific players; for example, if a bot repeatedly targets a player while ignoring other bots, it is a result of random chance. To address this specific case, the bots should be reprogrammed to ensure that a bot's choice of target is not random, but instead balanced between targeting players and other bots.

Another source of frustration was our strategy of providing only three of the seven games each week, and changing which three were available week to week. This was intended to provide variety and build anticipation for the next week's offerings. Three children (C1, C2, C4) experienced significant frustration when a game they had been enjoying the previous week was not available in the current week. This may have impacted the response to the SEAS Control and Choice sub-scale (**Figure 3**). A better solution might have been to add new games each week to keep the experience fresh, but not to retract any games.

Play with others was cited as motivational. Most children (C1, C3, C4), however, preferred not to talk with the other players. This was in part due to sensitivity to the headset; as noted by Grapel et al. (2015), hypersensitivity to sensory stimuli is frequent in (but not unique to) ASD. Noise-cancelling headphones are commonly and successfully used for mitigation of auditory hypersensitivity in children with ASD (Pfeiffer et al., 2019); at least one study, however, has found that a minority of children disliked and chose not to use headphones (Ikuta et al., 2016). Practical deployments should therefore provide alternative ways of communicating without requiring a headset, such as microphone and speakers. This preference for non-verbal communication may also be linked to deficits in speech-based communication found in some children with ASD (Williams White et al., 2007). We observed that children followed each other around the virtual world and played together, but at times, the lack of speech made it difficult for them to find each other, or even to see whether others were logged in to the game. This may explain the apparently contradictory results that players reported few Meaningful Interactions yet high Social Belonging in the SEAS (Figure 5.1); that is, they were happy to engage in an activity together even though (without speech) they could not directly interact. Exergames for children with ASD should therefore provide non-verbal means of communication for core tasks such as finding each other in the virtual world and negotiating which minigame to play.

This observation also indicates a need for caution in using exergames based on immersive virtual reality (e.g., *Beat Saber* on the Oculus Quest) in an ASD population, as virtual reality headsets may be difficult for some children with ASD to use. The CAVE approach used in Astrojumper (Finkelstein et al., 2010) removes the need for a headset but requires expensive equipment.

Several children (C1, C2, C4) described the games as too easy. This indicates a need to personalize the difficulty of the games to the abilities of the child. Older children may expect depth of play in exergames that matches that found in the other games they play. This may be particularly true of children with ASD, many of whom are frequent game players (Mazurek and Wenstrup, 2013).

7.2 Context of Gameplay

Richards et al. (2014) identified the importance of the context in which gamified systems are deployed to their success. The thematic analysis of **Section 6** indicates numerous ways in which context surrounding the use of the exergames was important.

The games were offered in the home environment. Parents and children appreciated the “safe space” that this provided, where there was no risk of judgement or bullying. This may be particularly important to children with ASD, who can experience difficulties with social interaction (Williams White et al., 2007) and low levels of physical fitness (Jones et al., 2017), both of which could make them vulnerable to bullying behaviours. Participants identified advantages of an in-school deployment; additional advantages would include lower logistical challenges, more structure to the program, and equity of access to families who cannot afford or do not have space for an exergaming bicycle. It would be critical in a school deployment, however, to maintain the children’s feeling of being in a safe space.

Parents identified benefits from the exergaming program to other aspects of their children’s lives, including increased confidence, more sharing of experiences through discussion of the games, and increase in physical activity outside of exergaming.

An unexpected result from the study was the children’s enthusiasm for the Garmin step tracker. The activity trackers were intended only to monitor participants’ activity outside of the exergames, but they rapidly became part of the intervention whereby children and parents collaborated and competed around increasing steps. It appears important, therefore, to consider how family can be included in increasing the children’s activity. To better integrate an exergame into the children’s lives, in-game rewards could be provided for out-of-game activity, in the style of *PiNiZoRo* (Stanley et al., 2010). For example, in-game coins could be awarded for steps tracked by a step counter. Such a mechanic might contribute to buy-in from parents, allaying reservations that exergaming is a form of screen time (Richards et al., 2014). This integration could both recognize the children’s motivation to use the step counter and also help to use the game as a gateway to other forms of physical activity.

The thematic analysis indicated that some children (C1, C2, C4) experienced a positive change in attitudes toward physical activity, a trend observed by Goodyear et al. (2021) in other online exercise interventions. This was seen in the enjoyment of the step counters and by increased fitness observed in the school.

7.3 Comparison to Other Neurodevelopmental Disorders

The *Liberi* exergames have been tested in earlier studies among children with CP (Hernandez et al., 2014; Knights et al., 2016), children with FASD (Schneider et al., 2020), and typically developing children (Kaos et al., 2018). In this section, we compare similarities and differences in findings for children with different neurodevelopmental disorders.

Children with CP, FASD, and ASD all found playing with others to be important, while group play was less uniformly motivational for typically developing children (Kaos et al., 2018). For example, in a 10-week study, children with CP played with others 69% of the time when others were online and played on average 35% longer when in a group. In a 10-week elementary school study of children with FASD, participants invented games to play together and found ways of cooperating versus bots in competitive games (Schneider et al., 2020). This desire to play with others may have been motivated by higher rates of social isolation seen in children with neurodevelopmental disorders such as ASD (Kwan et al., 2020). The children participating in this study were unique in wishing to play together but without using speech. As described above, this indicates an important requirement when designing for children with ASD to support devices that do not touch the skin and to support non-verbal communication.

The frustration we observed with this cohort during play was also seen among the children with FASD, where outbursts were at times so extreme as to require children to leave the play room. The children with ASD and children with FASD were frustrated over similar game issues, particularly perceived unfairness of the bots and rotation of games that caused previously available games to be removed. Frustration from these sources was not observed in children with CP or in a 6-week study of typically developing children (Kaos et al., 2018) and could be related to deficits in executive function shared between ASD (Demetriou et al., 2018) and FASD (Kingdon et al., 2016).

Some children (C1, C2, C4) in our sample described the games as overly easy. The *Liberi* games were explicitly designed to have low cognitive load to support children with CP, for whom simply carrying out pedalling motions can be cognitively demanding (Hernandez et al., 2013). While motor deficits are a cardinal feature of ASD (Fournier et al., 2010), persons with ASD do not generally have the same degree of motor deficits as those with CP, and hence the two groups might not experience equivalent cognitive loads when playing the same games. Failing to offer sufficient challenge will likely reduce adherence over the long term.

In conclusion, there are substantial similarities between ASD, FASD, and CP: all are neurodevelopmental disorders, all are associated with deficits in motor skills, and those affected tend to have lower participation in physical activity and a higher risk of social isolation than typically developing children. ASD and FASD are also associated with deficits in executive function. However, designing for ASD has its own very important requirements. It is therefore reasonable to design games for a broad umbrella of neurodevelopmental disorders, yet it is also critical to account for the specifics of ASD.

7.4 Limitations

Running for 6 weeks, the study was sufficiently long to determine participants' and families' perspectives about the games. This study was, however, limited by small numbers (five children, of whom four actively participated). This choice of sample size was driven by the challenges of recruiting, the logistics of dealing with an in-home study with a special population, and the availability of exergaming hardware to put in the children's homes. The cohort also had no female players, who may have had different experiences and perspectives on the exergames than the boys who participated. Because of this small sample, it was not possible to perform quantitative analysis to determine the health or other effects of game play. Working with small sample sizes is typical in studies of gaming for children with ASD (Baker, 2000; Winoto et al., 2016; Khowaja and Salim, 2019), and while such studies provide limited opportunity for quantitative data analysis, they can provide excellent qualitative results.

8 CONCLUSION

In this paper, we have explored the use of the *Liberi* exergaming system by five children with ASD over a 6-week period. We have discussed how while many children with ASD can (and do) play off-the-shelf games, it is nevertheless important to consider the abilities of these children when designing and deploying the games. Over the 6 weeks, four of the five participants engaged enthusiastically with the exergames, performing on average close to 1 hour of extra physical activity per week. Study with a larger cohort will be required, however, to draw definitive conclusions about the games' health benefits and long-term use.

Liberi's roots as a game designed for CP and later for FASD led to design decisions that matched requirements identified by other authors for games for children with ASD, such as measures to reduce demands on motor function, to reduce frustration, and to ease social interaction. Further requirements specific to children with ASD were identified in the study, such as the importance of supporting non-verbal communication, even for children who were fully verbal, and the value of games being seen as a safe space. Additionally, some children (C1, C2, C4) would have preferred more complexity and challenge in the games.

Parents were enthusiastic about the exergames, and identified positive effects in other aspects of the children's lives, such as increased confidence and increased willingness to undertake other forms of physical activity. Parents particularly encouraged school deployments of the games.

While this study was performed in the context of an exergame, our results are relevant to designers of games in general. Accessibility in games is important not just for "serious" games, but also to maintain the accessibility of games that are played solely for entertainment.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, to the extent possible as permitted by the authors' ethics review board.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board (HSREB). Written informed consent to participate in this study was obtained from the adult participants (parents), who also provided written consent for their children to participate. The parents were asked to review an assent form with their children, who were asked to then sign or print their name on the form.

AUTHOR CONTRIBUTIONS

NG, HC, and DS conceived of the study and wrote the funding application. NG, HC, BG, and DS designed the study. PZ coordinated patient recruitment and data collection. NG and BG led the acquisition and analysis of the quantitative data. NK facilitated the focus group and led the qualitative data analysis; HC and PZ were also involved in analyzing the qualitative data. NG and NK drafted the manuscript, with assistance from HC, PZ, and DS. All authors contributed to the interpretation of the data, critically reviewed the manuscript, and approved the submitted version.

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