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WonderFish: Design and Evaluation of a Social Exergame with Developed Bodily Interplay Dimensions for Children with ASD

Jing Li[*1,2,*], Xiongjie Yang[†1,*], Shi Qiu[‡1,*], Yuye Yang[§3], Ningning Zhao[¶1], Jun Hu[‖2], Emilia Barakova[**2], and Ting Han[††1]

[1]Shanghai Jiao Tong University, Shanghai, China
[2]Eindhoven University of Technology, Eindhoven, Netherlands
[3]Utrecht University, Utrecht, Netherlands
[*]Jing Li, Xiongjie Yang, and Shi Qiu contributed equally to this work as co-first authors.

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Abstract

Exergaming interventions have been shown to improve physical and cognitive functions in children with Autism Spectrum Disorder (ASD). However, designing exergames specifically targeting the motor and social skills of children with ASD remains an important open area. To address this gap, we developed WonderFish, a social exergame incorporating bodily interplay theory explicitly developed and designed to engage children with ASD alongside their parents. This paper presents the design and evaluation of WonderFish across four game modes, assessing its impact on children's motor and social skills, parent-child interactions, and user experience with eight pairs of children with ASD and their parents. We conducted qualitative and quantitative analyses, including game scores, physiological data, behavioural observations, surveys, and interviews. The results indicate that the game mechanism effectively elicited targeted motor and social behaviours during parent–child collaboration across the different modes. However, while parent-child dyads showed high levels of engagement, their interaction dynamics varied notably between the four modes.

Keywords: Social Exergame, Social Interaction, Children with ASD, Bodily Interplay, Computer-supported Collaboration

[*]j.li2@tue.nl, ORCID: 0000-0001-8105-5852
[†]justin$_{y}ang@sjtu.edu.cn$
[‡]Corresponding authors:qiushi11@sjtu.edu.cn, ORCID: 0000-0001-6699-1693
[§]yuyeyang66@gmail.com, ORCID: 0009-0009-6090-3854
[¶]123430910045@sjtu.edu.cn
[‖]Corresponding authors:j.hu@tue.nl, ORCID: 0000-0003-2714-6264
[**]e.i.barakova@tue.nl, ORCID: 0000-0001-5688-4878
[††]Corresponding authors: sjturesearch@gmail.com, ORCID: 0000-0001-7446-6733

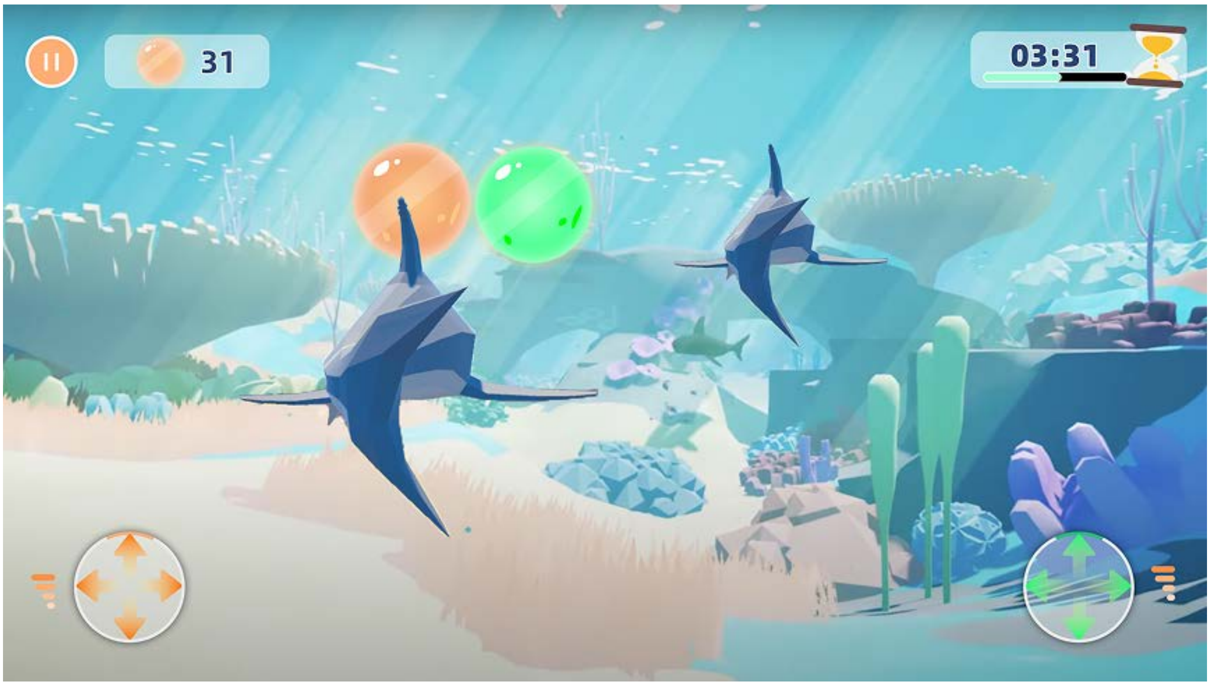

Figure 1: WonderFish User Interface Example.

1 INTRODUCTION

Children with Autism Spectrum Disorder (ASD) commonly experience differences in areas such as social interaction, emotional reciprocity, communication, fundamental motor skills and cognitive functions [Staples and Reid(2010), Association et al.(2013)]. Studies have suggested that limited levels of physical activity and late motor skills and fitness in children with ASD may exacerbate their social and emotional challenges [Lima et al.(2020)]. In view of this, research findings [Fang et al.(2019), Hilton et al.(2014), Lima et al.(2020)] suggest that the use of exergaming has the potential to be a valuable addition to standard interventions for children with ASD, for improving physical and cognitive functions in children with ASD. Exergames, which combine video gaming with physical activity, are a more engaging and safer form of exercise for children with ASD compared to ordinary physical activities [Benzing and Schmidt(2018)]. This enhanced appeal may positively influence engagement and adherence [Lima et al.(2020)]. Thus, many studies [Hilton et al.(2014), Lima et al.(2020)] have leveraged platforms like Wii and Kinect and examined effects of some off-the-shelf exergames like Kinect Sports with children with ASD. However, available exergames are not designed to support the needs of children with ASD, can impose high cognitive load and mismatched body interactions for them [Caro et al.(2017)]. There are a few exergame designs targeted to children with ASD, for instance, FroggyBobby [Caro et al.(2017)], and Liberi [Graham et al.(2022)], but they are mostly solitary exergames or playing with an on-screen avatar or virtual partner.

Social exergaming, which includes various components of social interaction within physical activities between multiple players, can improve not only motor skills but also social skills and engagement in children with ASD [Graham et al.(2022)]. Parents play a critical role in facilitating their children's physical activity, serving as important models and sources of support [Saksono et al.(2015)]. However, few studies have explored the design of social exergames for children with ASD that also actively engage their parents. This highlights the importance of developing social exergame mechanisms that involve parents in supporting the motor and social skills of children with ASD.

Bodily interplay theory, as proposed by Mueller et al. [Mueller et al.(2017)], offers a unique framework for designing bodily interactions between two players in social exergames. To target the motor and social skills of children with ASD—particularly imitation, cooperation, and turn-taking—we expanded the original bodily interplay dimension by adding a new dimension, 'synchronicity of bodily interplay.' This enabled us to develop a game mechanism with four distinct modes, aimed at engaging parents in supporting interventions targeting motor and social skills in children with ASD during social exergaming.

Based on this game mechanism, a collaborative social exergame—WonderFish (Fig. 1)—was designed for parents and children with ASD, aged 6–12 years. WonderFish features four unique game modes: Mode 1, "Imitation"; Mode 2, "Turn-based Imitation"; Mode 3, "Cooperation"; and Mode 4, "Turn-based Cooperation". In each mode, the two players collaborate on different body motions to control the fish's movements in virtual marine environments, aiming to collect as many bubbles as possible. WonderFish leverages computer vision technology to capture players' motions, providing an immersive gaming experience.

To evaluate WonderFish and its game mechanism, we conducted an empirical user study with eight families with children with ASD. We used a mixed-methods evaluation to compare the four game modes with the following research questions:

- Research question (RQ) 1: Can each game mode effectively train its targeted motor and social skills of children with ASD?
- Research question (RQ) 2: How does each game mode impact social interactions between children with ASD and their parents?
- Research question (RQ) 3: What are the perceptions of the user experience with WonderFish among children with ASD and their caregivers?

Our research findings are presented in Discussion section, which confirm our design and research contributions in three key aspects: (1) **The development of Bodily Interplay theory**: We advanced bodily interplay dimensions that were tailored for enhancing motor and social skills of children with ASD, and we implemented it in creating an exergame mechanism. (2) **A social exergame design**: We designed and deployed WonderFish - a social exergame leveraging mixed reality to facilitate collaboration between children with ASD and their parents; and (3) **An empirical user study**: We conducted user experiments with eight target groups and demonstrated our novel approach to evaluating user experience and interpersonal interactions in this computer-supported collaboration.

2 RELATED WORK

2.1 Social exergames for children with ASD

Social exergames for children with ASD are interactive games that combine physical activity with social interaction, helping improve both motor skills and social abilities [Fang et al.(2019), Graham et al.(2022), Lima et al.(2020)]. These games leverage the appeal of video games while encouraging movement [Yim and Graham(2007)], which can support cognitive development, motor coordination, and social engagement [Kaos et al.(2019)]. Research [Graham et al.(2022)] highlights that exergames can lead to improvements in physical fitness and social skills for children with ASD, fostering greater motivation and confidence through engaging, structured play.

Many off-the-shelf exergames - such as DDR [Anderson-Hanley et al.(2011)], Wii Fit [Dickinson and Place(2014)], and Xbox Kinect-based games [Golden and Getchell(2017)]- have been evaluated in studies among children with ASD, and have shown strong benefits in improving their physical and cognitive functions. For example, the exergame Liberi involving kinesthetic interaction within a virtual world has been shown to enhance physical activity and social connection with parents in children with ASD [Graham et al.(2022)]. The games include collaborative and competitive modes that allow children to play solo or with bots, which stand in for other players. It was originally developed for children with cerebral palsy to activate the movement of their hands and legs [Graham et al.(2022)]. Most of the exergames that have been tested with children with ASD were not specifically designed for this population[Graham et al.(2022)].

On the other hand, many review studies [Graham et al.(2022)] emphasize the importance of considering distinct requirements when designing social exergames for children with Autism Spectrum Disorder (ASD), as compared to those for typically developing (TD) children. Designing for ASD necessitates addressing specific challenges such as deficits in motor coordination, social interaction, and emotional reciprocity, which differ significantly from the needs of TD groups [Graham et al.(2022)]. For instance, Whyte et al. [Whyte et al.(2015)]

stress the importance of including opportunities in exergames for children with ASD to play with TD peers, as this can help them practice communication and social skills.

Although their effectiveness has been widely demonstrated, these social exergames for children with ASD have not been thoroughly studied in terms of social interaction. There have been few social exergame designed for children with ASD to play together with their caregivers. Nevertheless, some design guidelines have been proposed based on social interactions in exergaming - such as Bodily Interplay dimension [Mueller et al.(2017)] - and from interventions for children with ASD. Thus, we distill the following aspects that designers of social exergames for children with ASD should consider.

First of all, imitation and cooperation are two crucial social skills for children with ASD [Ingersoll(2008)]. Imitation helps children learn through observing and replicating others' behaviors, which is essential for developing communication and social interaction [Ingersoll(2008)]. Cooperation involves working with others, sharing, and taking turns, which are important for building relationships and engaging in social activities [Liebal et al.(2008)]. Both skills are foundational for improving social functioning and are commonly targeted in interventions for children with ASD[Ingersoll(2008)].

Second, among social skills that are core symptoms of autism spectrum disorder, turn-taking plays a fundamental role in regulating social interaction [Dawson et al.(2004)]. Turn-taking is an exchange of intention of an action between partners [David et al.(2020)]. It includes verbal or nonverbal behaviors such as orientating to social stimuli, rapid turning, avoiding overlaps, observing tasks that require a response, and responding appropriately [White et al.(2013)]. Turn-taking has been integrated into various therapeutic approaches, including communication and play-based interventions, to enhance social interaction and collaboration skills in children with ASD [Rieth et al.(2014)]. Previous research [Marker and Staiano(2015), Nekar et al.(2023)] on exergame design for children with developmental disabilities highlighted that cooperative exergaming showed significant improvements in terms of attention, anxiety and communication skills compared to competitive and solitary exergames. Thus, a cooperative turn-taking mechanism should be implemented and investigated in social exergaming for children with ASD and their caregivers.

In conclusion, few social exergames have been specifically developed for children with ASD to play with their caregivers. To address this gap and enhance exergame design for these target groups, applying principles from bodily interplay theory can inform exergaming interventions that support the development of imitation, cooperation, and turn-taking skills through physical interactions.

2.2 Bodily Interplay

"Bodily Interplay" refers to the extent to which bodies can act on and react to each other [Mueller et al.(2017)]. The Bodily Interplay Dimension, shown in Fig. 2, was extracted and developed from literature on social play from children's development [Frost et al.(2001)] and from Human-Computer Interaction (HCI) theories by Mueller et al. [Mueller et al.(2017)]. The key categories along the dimension can be used to investigate social phenomena among players in social exergames. The bodily interplay dimension has been instantiated in both the physical and virtual space and provided a structured understanding with regard to the many ways bodies can interact with one another in exertion games.

The "parallel exertion" category refers to situations where participants are exerting effort and mimicking each other but are acting independently. A typical example from Olympic sports is synchronized diving, in which each player performs their exertion actions independently of one another, yet they are aware of each other's actions [Vossen(2004)]. The other category is "interdependent exertion" that describes exertion experiences where participants actively use their bodies to interact physically, typically by either interfering with or assisting one another [Mueller et al.(2017)]. An example from traditional sports is the lifting in the line-out in rugby union, where players lift each other in the air to give them a height advantage for catching the ball [Mueller et al.(2017)]. The objective may be to take away the other player's points, or to provide as much support as possible. Interdependent Exertion describes exertion experiences in which players can affect each other's progress [Elias et al.(2012)].

Mueller et al. [Mueller et al.(2017)] also proposed subcategories along the bodily interplay dimensions for the physical and the virtual game space. For parallel exertion, these include: "knowing", where players are

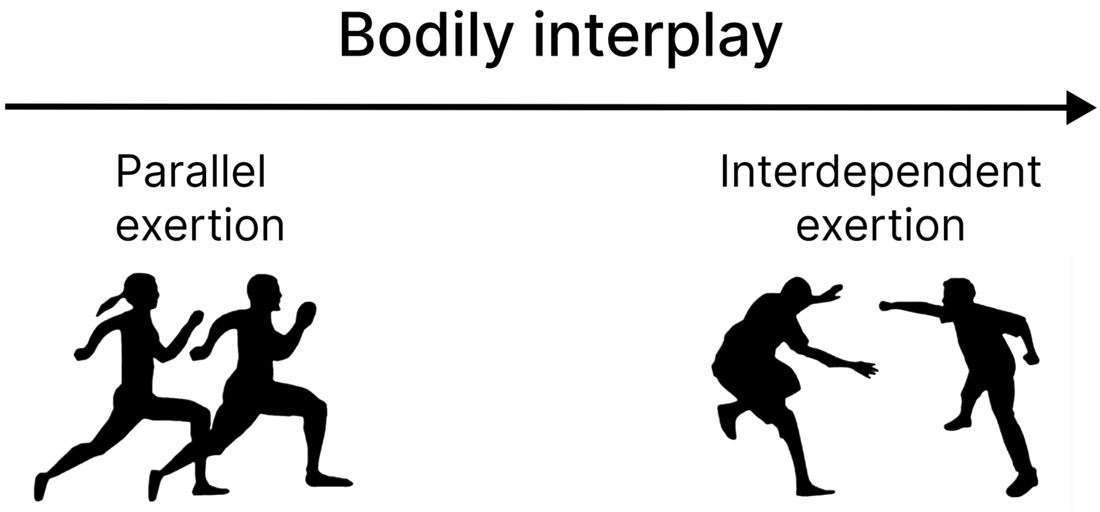

Figure 2: Bodily Interplay dimension by Mueller et al. [Mueller et al.(2017)]

aware of each other's movements; "comparing" where players compare each other's actions; and "matching", where players synchronize with each other in terms of rhythm and movement. For interdependent exertion, they defined: "shared object", where players share the same object and physically affect each other's exertion actions; "shared space", where players can influence how the other player moves within the game space; and "shared bodies", where players use their own bodies to directly control the other player's movements, fostering cooperation and physical engagement.

Prior computer-supported cooperative works have instantiated the Bodily Interplay theory in the design of social exergames. Yuan et al. [Yuan et al.(2024)] proposed an exergame system that fosters cooperation between older adults and their grandchildren by implementing interdependent exertion and creating shared objects, space, and body for the two players within the game environment. Another research by Park et al. [Park et al.(2013a)] focused on supporting interpersonal synchrony through parallel exertion, enabling players to match their movements in synchronous rhythms.

However, the full design potential of bodily interplay in social exergames for children with ASD remains largely unexplored. In particular, little is known about how parallel and interdependent exertion affect social interactions between children with ASD and other players during exergaming. Recognizing the importance of these bodily interplay dimensions, we aim to develop this theory and integrate it into the exergame design, which aims to enhance the motor and social skills of children with ASD.

3 DESIGN METHOD

To ensure the development of the exergame was guided by greater rigour, relevance and impact, we adopted a theory-driven design method [Cash(2018), Briggs(2006)] and an iterative design process [Li et al.(2020)]. Building on the foundation of social exergame design established in prior HCI works, we then incorporated bodily interplay theory [Mueller et al.(2017)] and intervention practices of turn-taking [Isaksen and Holth(2009), Bei et al.(2024)] to formulate our core game mechanisms, which are elaborated in Section 3.1. Subsequently, we tailored the physical exercises and user interactions to match the motor and social skill needs of children with ASD [Bei et al.(2024)].

We also sought expert input on the design of physical exercises for children with ASD. Occupational therapists and specialists from the Xingxing Qiao Special Care Centre reviewed our early concepts and movement library and advised which physical actions to prioritise for ASD interventions. They recommended integrating balance-oriented tasks and the directional coordination of body parts (e.g., lateral weight shifts, upper–lower limb coordination) to train whole-body coordination and support cognitive skills such as spatial orientation and response selection. We incorporated these recommendations into the four game modes and control mappings (see

Section 3.2).

To further ensure the exergame's suitability for children with ASD, we designed the elements of the Graphical User Interface (GUI) and Voice/Sound User Interface (VUI) in accordance with children's specific traits and preferences, as discussed in Section 3.2. Throughout development, we iterated the design through pilot user tests involving volunteers from the target group to verify its functionality, usability, and overall user experience (UX). Following these pilot tests, we identified and resolved several technical bugs and refined various design elements to further enhance the UX.

3.1 Developing of bodily interplay dimension for children with ASD

The dimension of bodily interplay aligns closely with targeted social interventions that aim to enhance imitation [Rogers et al.(2005)]and cooperation [Ziegler and Morrier(2022)] skills in children. In the context of parallel exertion, subcategories "knowing," "comparing," and "matching" are particularly effective in fostering imitation behaviors by encouraging children to observe and replicate others' actions [Rogers et al.(2005)]. In interdependent exertion, the three subcategories, which are "shared object," "shared space," and "shared bodies," serve to strengthen core social skills like social orienting and joint attention [Sharma et al.(2016)], as they require children to engage in coordinated, collaborative activities that emphasize mutual dependency and interaction. This dimension can suitably structure the design of social exergames for supporting children with ASD in their development of key social skills.

To enhance the design of exergames for children with ASD, we propose adding a new dimension for turn-taking exertion to the bodily interplay framework. Turn-taking, which involves alternating actions between participants, is a critical component for the development of motor and cognitive skills in children with ASD and is frequently incorporated into social and behavioral interventions [Rieth et al.(2014), Bei et al.(2024), Go et al.(2012)]. The common intervention techniques are turn-taking collaborative playing (e.g., throw, catch, pass the ball) [Zhao and Chen(2018)] and turn-taking imitation playing [Lee and Staggs(2021)].

Thus, we integrated turn-taking into the current dimension of bodily interplay and developed a game mechanism of social exergames, which is tailored to foster the development of versatile social and motor skills in children with ASD. The game mechanism is grounded in bodily interplay theory, as illustrated in Fig. 3.

This extension introduces a new dimension, termed "Synchronicity of bodily interplay", which distinguishes between bodily synchronous and turn-based interactions, since synchronization and turn-taking require different cognitive responses and bodily coordination [Schmidt et al.(2012)]. Exact bodily synchrony describes spontaneous temporal alignment (A and B move "in time"), and turn-taking describes sequential exchanges (A then B). They are both referred as synchronous interactions of dyads [Leclère et al.(2014)]. We operationalised synchronicity as a tunable mechanic parameter that controls the required degree of temporal coupling and correspondence between partners' actions, spanning parallel and interdependent play through synchronous/co-operative to strict turn-taking.

Based on the two dimensions - Parallel and Interdependent - of bodily interplay, and Synchronicity of bodily interplay, we propose the formation of four interactive gaming modes. These modes aim to cultivate the individual as well as the combination of three key social skills - imitation, cooperation, and turn-taking - through various forms of bodily interplay between two players. The following outlines the differences in the game mechanisms across each mode:

Mode 1: In the top-left of Fig. 3, parallel aligns with synchrony to form the "Imitation" mode. Two players are expected to perform the same movements synchronously, encouraging them to mirror each other's actions during gameplay.

Mode 2: In the top-right of Fig. 3, parallel pairs with turn-taking to form the "Turn-based Imitation" mode. Two players take turns completing the same movement, enabling one player to imitate the other's movements in succession.

Mode 3: In the bottom-left of Fig. 3, the Interdependent dimension aligns with synchrony to create the "Cooperation" Mode. Both players have a shared object, space and body within the digital game, performing distinct sets of movements to collaboratively control one digital entity and achieve a common objective.

Mode 4: In the bottom-right of Fig. 3, the Interdependent dimension pairs with turn-taking to form the "Turn-based Cooperation" Mode. Similar to Mode 3, both players have a shared object, space, and body within the digital game; however, in this mode, they take turns executing their movements, reinforcing individual responsibility within a collaborative effort.

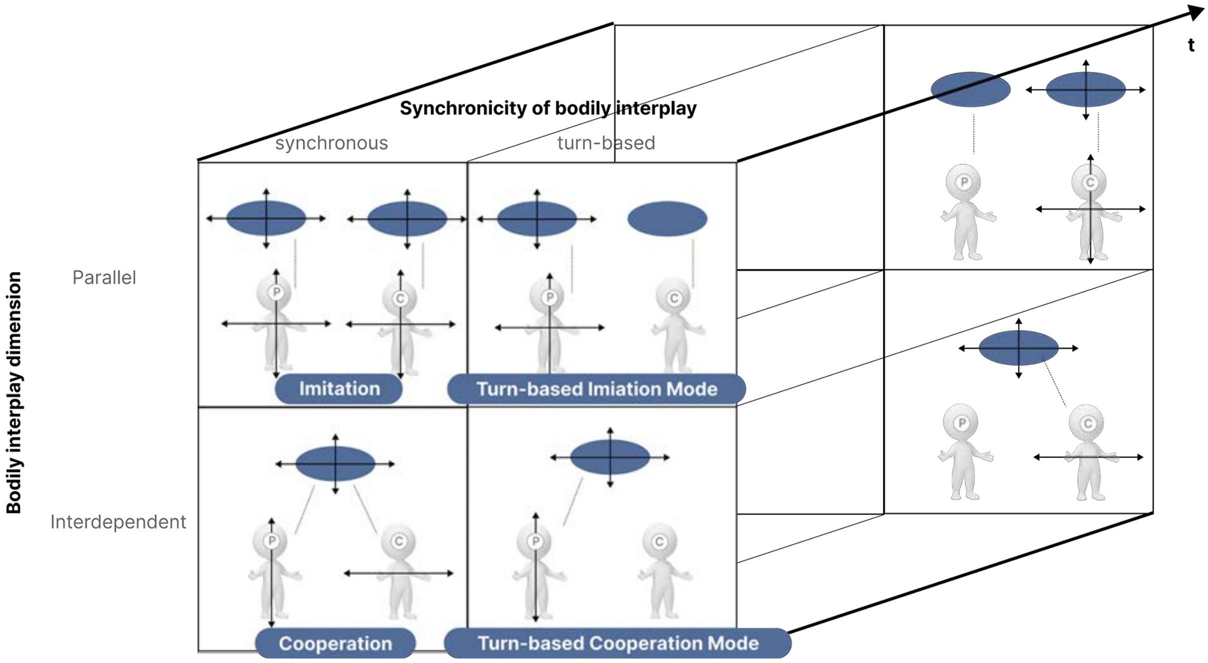

Figure 3: Game mechanism of social exergame design for children with ASD, with two dimensions that are Bodily interplay dimension and Synchronicity of bodily interplay.

3.2 Design of WonderFish

3.2.1 User Interaction (UI) and User Experience (UX) Design

In WonderFish, the child player is paired with their parent, facing toward the screen to perform coordinated physical movements, such as leaning left or right and raising or lowering their arms and body, in order to control the direction and movement of an avatar, represented by a fish, within a digital marine environment. These types of motions are commonly targeted in interventions for children with ASD in terms of developing their balance, bilateral coordination, postural control, whole-body coordination and fine motor skills [Bremer et al.(2015), Fournier et al.(2010), Provost et al.(2007)]. As they advance through three different ocean spaces, bubbles appear in sequence, and the objective is to guide the fish to collect as many bubbles as possible within a 5-minute time frame for each round. As outlined in our game mechanism (Fig. 3), four distinct game modes are demonstrated in Fig. 4.

Mode 1: This is the "Imitation" mode, designed with the goal of encouraging children to imitate the motions demonstrated by the exergame and their parents. The child's movements control a small fish, while the parent's movements control a larger fish, guiding them both to swim up, down, left, and right. The two fish swim side by side, with each responsible for collecting their own bubbles which are indicated with different colors. Players have 10 seconds to maneuver and position their fish to 'bump' the bubbles before new bubbles appear in different locations. As illustrated in Mode 1 (Fig. 4), both the parent and child can see their respective control wheels on the screen, indicating the required movements to guide their coordination and body awareness.

Mode 2: This mode is referred to as "Turn-based Imitation", where the child and parent players are expected to take turns completing their exercise. The movements remain the same as in Mode 1. The child still controls the small fish, while the parent controls the large fish. However, the two fish alternate every 5 seconds to "bump" the bubbles. When it is one fish's turn, the other becomes semi-transparent and is unable to interact with the bubbles. The player's control wheel on the screen lights up when it is their turn. This setup is intended to help the child develop an understanding of turn-taking by practicing it during gameplay.

Mode 3: This mode is called "Cooperation". In this mode, the child and parent players are tasked with

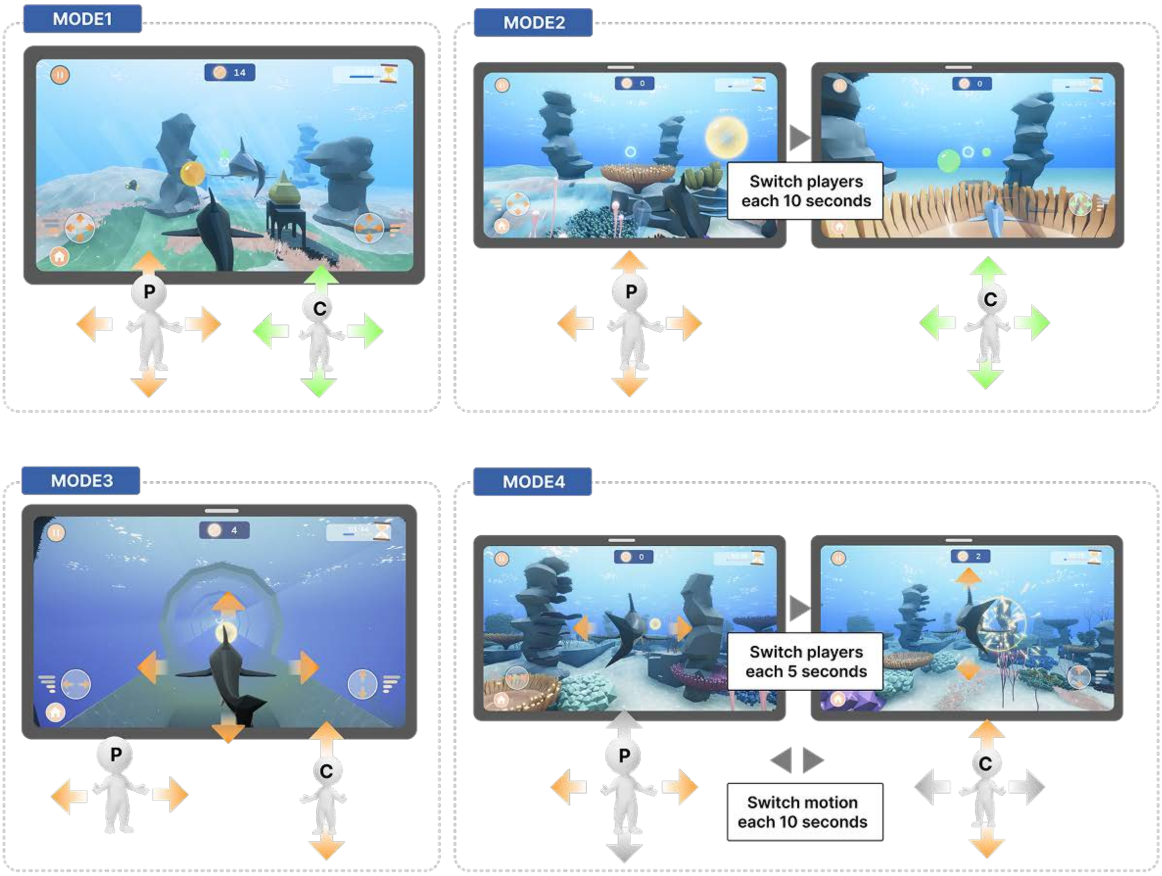

Figure 4: Four different game modes with UI and UX instruction.

jointly controlling a single fish simultaneously. One player manages the up and down movement, while the other controls the left and right movement to collect bubbles, shown in Mode 3 (Fig. 4). Every 10 seconds, the players switch their directional controls to guide the fish toward the next bubble. This collaborative setup allows the child and parent to share control over a single digital entity, encouraging the child player to work together with their parent while also allowing each to play independently in the game.

Mode 4: This mode is called "Turn-based Cooperation". Similar to Mode 3, the child and parent players share control of a single fish. However, in this mode, one player starts by positioning the fish in one direction, either up and down or left and right, aiming it towards the bubble. After 5 seconds, the other player takes over control to complete the movement in the other direction, as illustrated in Mode 4 (Fig. 4). Each coordination sequence lasts 10 seconds per bubble, with each player having 5 seconds to control the fish, taking turns. The success of collecting the bubble depends on how well the first player positions the fish, affecting whether the second player can complete the task.

During each game mode, the bubbles collected by both players are counted and converted into game points. At the end of each mode, a summary of two players' collaborative results will be displayed. An example result user interface is shown in Fig. 5. It displays the total number of bubbles collected, the percentage of collected bubbles out of all that appeared, the maximum combo count, and the game score for this mode. The algorithms for calculating the game score in each mode are explained below. Different calculations are applied due to the varying amount of bubbles that appear across different modes. If it's mode 1:

$$score = \left(\frac{CollectedAllBubbles}{2} \times 10\right) + \left(\frac{percentage}{2} \times maxCombo \times 10\right) \tag{1}$$

Or else:

$$score = (CollectedAllBubbles \times 10) + \left(\frac{percentage}{2} \times maxCombo \times 10\right) \tag{2}$$

Figure 5: Example of game result user interface (points=score).

3.2.2 System implementation

Motion capture technologies used in exergames are crucial for tracking and analyzing the physical movements of players in real-time. These technologies enable the game to interact with players' body movements, helping to create immersive and physically engaging experiences. There are some commonly used motion capture technologies in exergames like RGB-D cameras [Zhang(2012)], Inertial Measurement Units (IMUs) [Fang et al.(2023)], Optical Motion Capture [Menache(2000)], and Infrared Sensors [Al-Fahoum et al.(2013)]. Most of them require precise motion capture, which would necessitate multiple devices, introducing technical complexity and usability challenges that could hinder accessibility and comfort. Given that our target users are children with ASD, they tend to avoid wearing additional physical devices due to sensory sensitivity. Thus, computer vision presents a more practical and user-friendly solution for this application. In addition, this technology offers ease of deployment and a quick and low-cost setup that meets the design requirements.

WonderFish was developed using Unity3D and the MediaPipe plugin [1], optimized to run on macOS. MediaPipe does not utilize a depth camera like the Kinect system, but it produces more accurate results with a smaller standard error in joint angle estimations compared to Kinect-based tracking [Lugaresi et al.(2019)]. WonderFish leverages MediaPipe's capabilities to transform body movements into interactive controls within the game. Within WonderFish, this framework captures key body landmarks, which it then translates into commands for in-game movements, allowing players to control their virtual avatar through simple, intuitive gestures.

The final system was deployed on a 2023 MacBook. A 1080p wide-angle webcam with a 120° field of view is connected to support real-time motion tracking. As shown in Fig. 6, the system utilizes the webcam to capture the player's body position and relays this information to MediaPipe's pose estimation engine to generate a list of pose landmarks. This data is then processed through pose estimation algorithms to determine motions such as arm raises or body turns. A set of predefined mapping rules governs the interactions between players' motions and the fish's movements.

Fish's horizontal movements are controlled by calculating the slope of the line connecting the torso's center point and the waist's center point. The formula is presented below. Here, x and y correspond to the respective MediaPipe landmarks shown in Fig. 6.

$$angleX = \tan^{-1}\left(\frac{\frac{y_{24}+y_{23}}{2} - \frac{y_{12}+y_{11}}{2}}{\frac{x_{24}+x_{23}}{2} - \frac{x_{12}+x_{11}}{2}}\right) \cdot \frac{180}{\pi} - 90 \tag{3}$$

Fish's vertical movements are linked to the angle between the player's arm and torso. The formula is presented below:

$$angleX = \cos^{-1}\left(\frac{(x_{11}-x_{23})(x_{13}-x_{11}) + (y_{11}-y_{23})(y_{13}-y_{11})}{\sqrt{(x_{11}-x_{23})^2 + (y_{11}-y_{23})^2} \cdot \sqrt{(x_{13}-x_{11})^2 + (y_{13}-y_{11})^2}}\right) \cdot \frac{180}{\pi} - 90 \tag{4}$$

[1] https://chuoling.github.io/mediapipe/

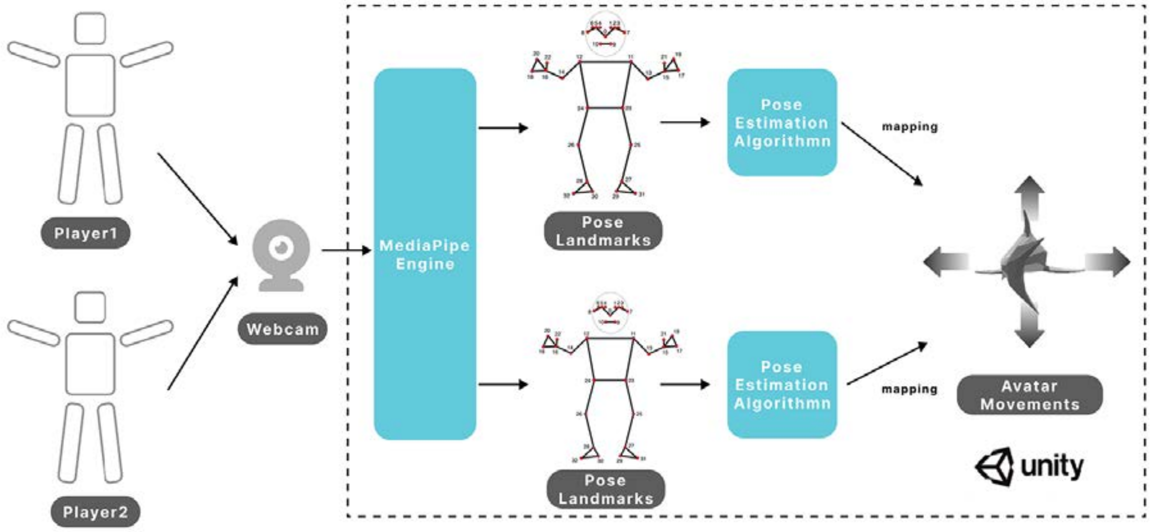

Figure 6: Rationale of motion capture in WonderFish.

Then *angle x* and *angle y* are mapped to a distance using the linear mapping formula below:

$$mappedValue = outputMin + \frac{(inputValue - inputMin)(outputMax - outputMin))}{inputMax - inputMin} \tag{5}$$

These mappings are handled through simple condition checks but could be expanded with machine learning algorithms for more complex actions. When players raise an arm and lean their bodies, the game calculates the angles for each person, then maps and combines them differently to move the fish within the marine environment according to the four different game mechanisms. Once computed, the control parameters are passed to the Unity engine, where they are rendered in real time, allowing the player to see their movements directly reflected in the virtual world. The three 3D undersea marine environments in WonderFish are sourced from the Unity Asset Store [2].

4 EVALUATION METHOD

WonderFish was evaluated through a structured user-testing design to assess the effectiveness of its game mechanics in fostering targeted motor and social skills in children with ASD. A within-subject study design with a small sample size was employed, allowing for comparison across four game modes—Imitation, Turn-based Imitation, Cooperation, and Turn-based Cooperation—to address three core research questions.

This design evaluation approach was aimed at examining the efficacy of WonderFish's design in promoting motor and social skill development, as well as its overall usability and engagement for children with ASD.

4.1 Participants

Eight families with children with ASD were recruited from Xingxing Qiao special care centre for neurodiverse children in Ningbo city, China. The therapists at the care centre pre-screened children who met the inclusion criteria for us. Then, researchers introduced the WonderFish experiment to these families and recruited all parent-child dyads who were interested in joining the experiment and also met the inclusion criteria of parent participants. Before the experiment date, we obtained obtained written parental consent and child assent. Each dyad consisted of one child and one of their parents, who participated together in the user experiment of WonderFish. All child participants ($M = 7.5$, $SD = 1.2$; $Female = 1$, $Male = 7$) met the following inclusion criteria:

1. Aged between 6 and 1O years old.
2. Full-scale IQ above 70.

[2] https://assetstore.unity.com/packages/3d/environments/landscapes/thalassophobia-stylized-oceans-192227

Table 1: Participant groups and demographic information

Participant Group (ID)	Parent (ID)	Parent Gender	Parent Age	Child (ID)	Child gender	Child Age	ASD severity
Group 1	P1	Female	35	C1	Male	7	Level 1
Group 2	P2	Female	32	C2	Male	8	Level 2
Group 3	P3	Female	40	C3	Male	10	Level 1
Group 4	P4	Female	38	C4	Male	7	Level 1
Group 5	P5	Male	42	C5	Female	8	Level 1
Group 6	P6	Female	37	C6	Male	7	Level 2
Group 7	P7	Female	38	C7	Male	7	Level 2
Group 8	P8	Male	40	C8	Male	6	Level 2

3. Clinician-Diagnosed with a level 1 or level 2 ASD severity according to the DSM-IV criteria [Association et al.(2013)].
4. No cardiovascular disease.
5. No medically diagnosed cognitive, motor or visual impairments.

According to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-IV), the severity of Autism Spectrum Disorder (ASD) is classified into three levels: Level 1 (requiring support), Level 2 (requiring substantial support), and Level 3 (requiring very substantial support) [Association et al.(2013)]. In this study, ASD severity was determined based on clinical diagnostic records from licensed clinicians, as reported by parents. Every group completed the study and received 200-yuan compensation for an experiment that lasted approximately 30 minutes. Detailed participant information is shown in Table 1.

4.2 Procedure

The research protocol and data collection procedures received approval from the Research Ethics Committee of Shanghai Jiao Tong University (ID: K20240331). User experiments took place in a lecture room at the Xingxing Qiao Special Care Centre, which was outfitted with a 100-inch standing TV screen, as shown in Fig. 7. A webcam mounted on the TV screen captured the movements of both participants in the room. During the experiment, the child and parent players faced the TV screen. The child player stayed on the right side, and the parent player stayed on the left side with a taped line on the floor delineating the movement space for each player. This setup facilitated clear spatial organization and optimized motion capture for the study.

As illustrated in Fig. 8, prior to the experiment, each participant group was given a brief overview of the study's purpose and procedures. The parent, who also served as the child's guardian, signed an informed consent form and received a detailed explanation of the experimental protocol and equipment usage. Both the child and parent then donned Polar H10 heart rate monitors[3], which were placed around their chests. A trained instructor provided verbal and physical instructions, guiding the participants through the gameplay mechanics and explaining the scoring system.

After calibrating the camera, the participants completed a one-minute trial run of WonderFish. To control for sequence effects among different game modes, the eight participant groups played the four modes in a randomized order. Each mode lasted 5 minutes and featured three different marine environments. Throughout the experiment, an instructor remained in the room to launch the game, record data using a video recorder and the Polar H10 device, and provide technical assistance if needed.

Following each mode, the parent completed a questionnaire and, if necessary, assisted the child with their questionnaire. This process was repeated for all four modes. All participant groups completed the four exergame modes without interruption. However, variations in completion time were observed for the questionnaires. The four modes of WonderFish were performed in a randomized order to avoid carry-over effects.

After completing the four exergaming modes and corresponding questionnaires, the instructor terminated the video and Polar H10 recording. The parent and child participants were then invited to participate in a semi-structured interview to provide feedback on their user experience. All the interviews were audio-recorded.

[3] https://www.polar.com/en/sensors/h10-heart-rate-sensor

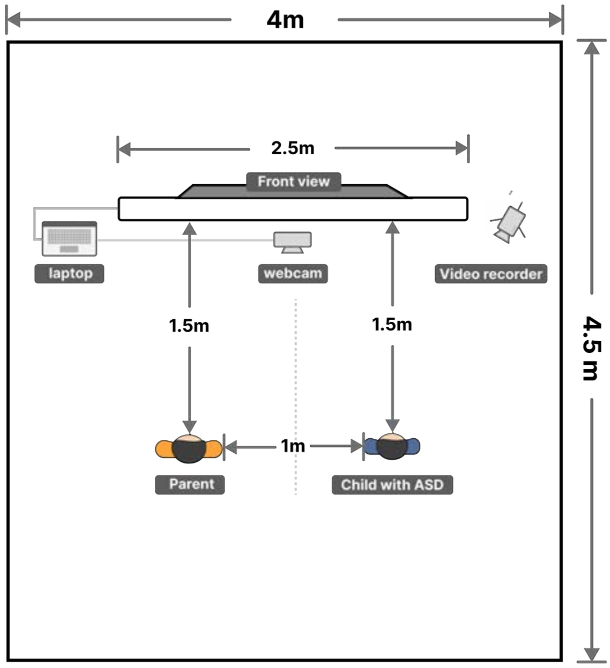

Figure 7: Experimental Setup.

To mitigate fatigue/overexertion, the session was structured into short blocks (5 mins) by game mode with a planned break between modes, during which the child and parent completed brief questionnaires and rested. Participation was voluntary, and families could pause or discontinue the session at any time without penalty.

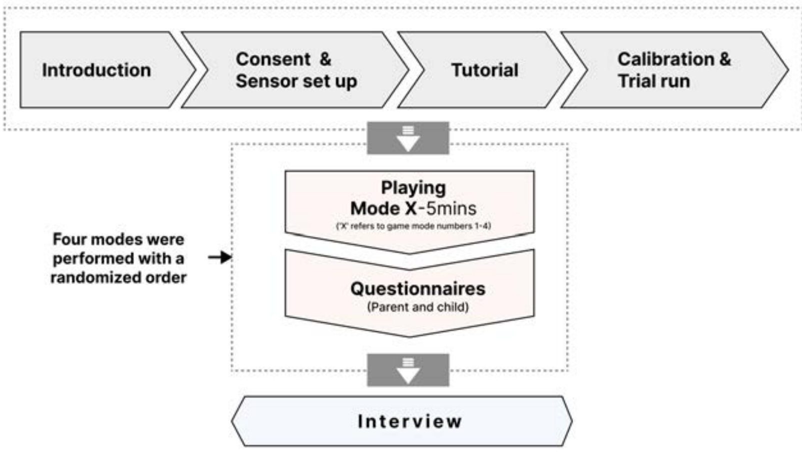

Figure 8: Experimental Procedure.

4.3 Data Collection

Given the cognitive and communication characteristics of children with ASD, traditional data collection methods typically used with TD children or adults may present challenges. Many studies in HCI [Qiu et al.(2021), Sharma and Giannakos(2021)] suggest that simplified, visual-based questionnaires, caregiver-provided subjective reports, behavioral observations, and physiological data offer more effective approaches for gathering information from children with ASD. These methods are often favored due to their efficiency, accuracy, and objectivity in capturing relevant data for this population.

Thus, we employed a mixed-methods approach to collect both quantitative and qualitative data in evaluating the intervention's effectiveness. For quantitative data, we captured objective measures, such as stress, autonomic responses, and parasympathetic activity, via heart rate variability (HRV) metrics recorded through the Polar H10 sensor and the Polar Sensor Logger application [4], on mobile devices. HRV serves as an indicator of autonomic regulation during social interactions, offering insights into how children with ASD respond to stimuli or stressors [Reisinger et al.(2024)]. In addition to recording HRV data from the children, we collected HRV metrics from their parents to facilitate dyadic interaction analysis.

Video recordings were collected throughout gameplay to analyze social interactions between children and parents, as well as to assess the physical motions of children with ASD through behavioral coding. Additionally, game scores for each game mode were recorded and stored on the game device to measure the impact of each mode on the motor and social skills of children with ASD.

Subjective data was collected to investigate the user experience of children with ASD. Children were asked to answer a simplified questionnaire (Appendix 1) based on Self-Reported Experiences of Activity Settings (SEAS) [King et al.(2014)], which included two questions with graphic symbol support after each game mode to assess emotion during the game. This questionnaire was adapted to accommodate participants' cognitive profiles and comprehension needs. Additionally, due to self-reporting challenges for children with ASD and to obtain a reliability assessment of children's UX, we developed a parent-report UX questionnaire (Appendix 2), which adapts key aspects for evaluating UX in immersive virtual environments [Tcha-Tokey et al.(2016)]. After completing all game modes, a semi-structured interview was conducted and recorded with each participant group. This interview aimed to capture users' experience regarding WonderFish, as well as their suggestions for future design iterations (see Appendix 3 for the detailed interview guide).

4.4 Data Analysis

We employed a convergent parallel mixed-methods design. Quantitative (physiological/behavioral metrics) and qualitative data (observations and interviews) were collected concurrently and analyzed independently. We then merged the results to compare areas of convergence, complementarity, and divergence, yielding an integrated understanding of effectiveness and user experience.

4.4.1 Quantitative Data

The raw electrocardiogram (ECG) signals were processed in Kubios HRV Scientific software [5] to correct artifact and extract time-domain and frequency-domain HRV parameters [Tarvainen et al.(2014)]. Within Kubios, R-waves were automatically detected using a built-in QRS detection algorithm based on the Pan–Tompkins method [Pan and Tompkins(2007)], which includes a preprocessing stage involving bandpass filtering ranging from 5 to 25 Hz to reduce baseline drift, power line interference, and other noise. Once artefact beats are detected, Kubios replaces them with values obtained from cubic spline interpolation of neighboring normal beats. For time-domain HRV data, we set a two-minute window and calculated it every second to get the Root Mean Square of Successive Differences (RMSSD) sample points.

Given the small sample size (N = 8), which may compromise the stability of repeated-measures ANOVA, the Friedman test was used to evaluate within-subject effects for (1) overall game score- the success Rate, (2) questionnaire responses, (3) the frequency of Dyadic Parent-Child Interaction Coding System (DIPCS) [Eyberg et al.(2004)] behavior codes, (4) HRV measures.

Because the game modes used different native scoring schemes, we computed a common performance metric - the success rate - defined as the percentage of bubbles popped:

$$SuccessRate(\%) = \frac{Numberofbubblespopped}{Numberofbubblespresented} \times 100\% \tag{6}$$

Additionally, descriptive analyses of the behavioral coding were conducted, focusing on the frequency of specific behaviors in the four game modes. To evaluate whether the design stimulates the intended motions and behaviors from children under each game mode, we conducted behavioral coding with three codes: "Imitation", "Cooperation", and "Turn-taking". The behavioral coding scheme is attached in Appendix 4. The other descriptive analyses are performed on DIPCS codes, to understand how different modes influenced social interaction

[4] https://play.google.com/store/apps/details?id=com.j_ware.polarsensorlogger&hl=en
[5] https://www.kubios.com/hrv-scientific/

patterns in parent-child dyads.

Results from all statistical analyses are reported with 95% confidence intervals, providing a clear indication of the precision of the estimates. Effect sizes were calculated to assess the practical significance of the findings, offering insight into the magnitude of the observed effects. To control for potential Type I errors arising from multiple comparisons, Bonferroni corrections were applied, ensuring that the findings remained statistically rigorous. All analyses were conducted using SPSS (version 29.0.1.0). In addition, the visualizations of the data were primarily created using R (version 4.4.1).

4.4.2 Qualitative Data

For interview data, we conducted a qualitative content analysis in MAXQDA software. Two primary authors first developed a hybrid codebook based on interview questions (deductive UX categories aligned with our RQs and inductive codes emerging from the data), independently coded all transcripts, and then resolved discrepancies by discussion with a third researcher. We then grouped codes into categories (e.g., engagement facilitators, difficulty drivers, feature requests) and summarized their prevalence across families to produce the user-experience themes reported in Section 5.2.1.

In the same approach, we investigated social interactions between children with ASD and their parents. We coded videos on parent-child interactions during each game mode. We used the coding scheme based on DPICS [Eyberg et al.(2004)], which is a validated coding system for assessing parent-child interaction in children with ASD[Bauman(2015)]. All video and audio recordings were imported and coded in MAXQDA software. The videos were reviewed and coded by two primary authors. The videos were analyzed to assess behaviors related to imitation, cooperation, and turn-taking within the game mechanism (Fig. 3). Each author coded the videos independently; any discrepancies in coding were discussed and reconciled with input from a third, experienced qualitative analysis coder to ensure accuracy and consistency. Inter-rater reliability was evaluated using intraclass correlation coefficients (ICCs) derived from a two-way mixed-effects model with a consistency definition [Koo and Li(2016)]. For the overall DIPCS codes, the ICC for single measures was $ICC = 0.991$, 95% CI $[0.990, 0.993]$, $p < 0.001$, and the ICC for average measures was $ICC = 0.996$, 95% CI $[0.995, 0.996]$, $p < 0.001$, indicating excellent agreement between coders. For the targeted codes, the ICC for single measures was $ICC = 0.865$, 95% CI $[0.814, 0.903]$, $p < 0.001$, and the ICC for average measures was $ICC = 0.928$, 95% CI $[0.897, 0.949]$, $p < 0.001$, reflecting excellent inter-rater agreement.

The behavior coding and HRV data were analyzed and visualized alongside time stamps for further qualitative analysis. One of the HRV metrics visualized was RMSSD for both parents and children. RMSSD is a widely used time-domain measure for assessing heart rate variability, commonly associated with engagement and responsiveness in interactive settings [Reisinger et al.(2024)]. Generally, a moderate-to-high or increased RMSSD could indicate a calm and comfortable engagement, in which the participant is relaxing, while lower or reduced RMSSD values can reflect focused concentration or instances of tension [Shaffer and Ginsberg(2017), Park et al.(2013b)]. A pronounced fluctuation in RMSSD indicates strong emotional shifts, tense interactions in social scenarios, or changes in physical exertion [Kim et al.(2018), Laborde et al.(2017)]. Synchronous fluctuations in RMSSD between two people suggest a degree of social or emotional alignment [Palumbo et al.(2017), Timmons et al.(2015)]. This analysis offers insights into the physiological states of both players during exergaming, as well as the relationship between physiological and behavioral data. RMSSD variations help elucidate the effects of exergaming interventions, the dynamics of parent-child interactions, and engagement levels throughout the exergame.

Finally, we integrated qualitative video codes and quantitative (game scores, surveys, HRV) strands by aligning time-stamped observations with RMSSD series and comparing patterns at the mode level (see Section 5.2.2), providing a convergent interpretation of effects and mechanisms.

Table 2: Descriptive statistics for the frequency of "Imitation", "Cooperation" and "Turn-taking" codes

Variable	Mode 1		Mode 2		Mode 3		Mode 4	
	M	SD	M	SD	M	SD	M	SD
Imitation	24.25	4.83	17.13	1.96	2.5	1.93	3.5	2.56
Cooperation	2	2.56	1.13	1.13	26.38	2.45	24.75	4.5
Turn-taking	0	0	29.25	3.45	0	0	42.25	14.79

Mode 1: Imitation Mode; Mode 2: Turn-based Imitation Mode; Mode 3: Cooperation Mode; Mode 4: Turn-based Cooperation Mode.

Table 3: Friedman test results for success rate

Measure	Mode 1		Mode 2		Mode 3		Mode 4			
	M	SD	M	SD	M	SD	M	SD	χ^2 (3, N=8)	p-value
Success Rate	63% a	10%	73%	6%	89% b	13%	69%	16%	11.40	$< 0.01^*$

* indicates $p < 0.05$; 'a' indicates a significant difference compared to Mode 3, and 'b' indicates a significant difference compared to Mode 4. Pairwise comparisons were Bonferroni corrected. Mode 1: Imitation Mode; Mode 2: Turn-based Imitation Mode; Mode 3: Cooperation Mode; Mode 4: Turn-based Cooperation Mode.

5 RESULTS

5.1 Quantitative results

5.1.1 Analysis on targeted motor and social skills

Table 2 summarizes the descriptive statistics for the frequency of motions of child participants that fall in "Imitation", "Cooperation", and "Turn-taking" behavioral codes under four modes.

"Imitation" behaviors were mostly observed in the imitation-targeted Mode 1 (M = 24.25, SD = 4.83), and Mode 2 (M = 17.13, SD = 1.96), while they also occurred in Mode 3 (M = 2.50, SD = 1.93) and Mode 4 (M = 3.50, SD = 2.56). "Cooperation" behaviors occurred most frequently in the cooperation-targeted modes, such as Mode 3 (M = 26.38, SD = 2.45), and Mode 4 (M = 24.75, SD = 4.5). On the other hand, they were rarely observed in Mode 1 (M = 2.00, SD = 2.56) and Mode 2 (M = 1.13, SD = 1.13). "Turn-taking" behaviors were only elicited in turn-based modes, such as Mode 4 (M = 42.25, SD = 14.79), followed by Mode 2 (M = 29.25, SD = 3.45). Modes 1 (Imitation Mode) and 3 (Cooperation Mode) exhibited no engagement in turn-taking activities. The descriptive analysis demonstrates distinct patterns in frequencies of imitative, cooperative and turn-taking behaviors across four modes. All four modes elicited their targeted motions and behaviors from participants.

The game success rate, determined by the percentage of bubbles collected in each mode, serves as an indicator of children's motor performance across different game modes. It also provides insight into the collaboration between the child and parent players. The Friedman test was conducted on the success rate results (See Table 3). The analysis using the Friedman test indicated a significant difference in game performance across the four game modes, $\chi^2(3, N = 8) = 11.40$, $p = .01$. Post-hoc pairwise comparisons with Bonferroni correction revealed that percentages in Mode 1 ($M = 63\%, SD = 10\%$) are significantly lower than those in Mode 3 ($M = 89\%, SD = 13\%$). Success rate in Mode 3 is significantly higher than those in Mode 4 ($M = 69\%, SD = 16\%$).

5.1.2 Analysis on social interaction between child and parent

The descriptive analysis of DPICS behavior coding in four game modes, focusing on parent-child interaction dynamics, is summarized in Table 4.

Positive interactions include codes of "Positive affect", "Encouragement", and "Praise". Parents showed more instances of "Positive affect" across four game modes compared to children. Specifically, the highest frequency of "Positive affect" was observed in parents during Mode 3 (M = 15.88, SD = 7.04), which remained consistent throughout the four modes, while children demonstrated a slightly lower level of "Positive affect", with the highest

Table 4: Descriptive analysis results of behavior codes using DPICS code scheme

DPICS code scheme	Mode 1		Mode 2		Mode 3		Mode 4	
	M	SD	M	SD	M	SD	M	SD
Distracton (P)	0	0	0	0	0	0	0	0
Distraction (C)	0	0	0	0	0	0	0	0
Physical negative (P)	0.13	0.35	0	0	0	0	0.38	0.74
Physical negative (C)	1.88	2.36	1.63	2	0.38	0.52	1.88	2.7
Ignore and non compliance (P)	0.63	0.92	0.38	0.74	1.5	1.69	0.88	1.13
Ignore and non compliance (C)	3	2.73	1	0.76	1.75	1.67	1.88	1.96
Verbal negative (P)	3.25	3.58	1.25	2.05	0.88	0.99	2.13	2.23
Verbal negative (C)	3.75	5.31	1.5	2	1.38	1.69	2.38	1.6
Positive affect (P)	14.13	9.78	14.63	5.71	15.88	7.04	14.5	7.39
Positive affect (C)	12.25	8.36	10.38	7.25	10	6.19	8.63	6.02
Command and compliance (P)	11.5	12.46	17.63	13.03	19.63	14.11	18.75	6.73
Command and compliance (C)	8.38	9.18	16	11.83	19.88	11.22	17.13	7.47
Question (P)	0.63	0.92	0.38	0.52	0.5	0.76	0.5	1.07
Question (C)	1.38	1.3	2.25	1.91	0.38	0.52	0.25	0.46
Reflection (P)	1.75	2.38	0.88	0.99	0.5	1.07	0.38	0.52
Reflection (C)	0.13	0.35	0.38	0.74	0.13	0.35	0	0
Encouragement (P)	0.88	0.83	2	1.93	1.13	1.36	0.63	0.74
Praise (P)	3.88	3.64	3.38	2.72	3.5	2.98	5.63	5.04
Statement (P)	8.88	3.14	12.25	6.32	7.38	3.54	9.88	3.87
Statement (C)	4.13	3	4.25	2.19	6	8.88	2.63	2.5

The notation (P) indicates behaviors coded from parents within the game, while (C) indicates behaviors coded from children within the game. Mode 1: Imitation Mode; Mode 2: Turn-based Imitation mode; Mode 3: Cooperation Mode; Mode 4: Turn-based Cooperation Mode.

in Mode 1 (M = 12.25, SD = 8.36). "Praise" and "Encouragement" were observed only in parents. Parents praised their children more often than they encouraged them, with the highest frequency of "Praise" occurring in Game 4 (M = 5.63, SD = 5.04).

"Command and compliance" behaviors also had a higher frequency for both parents and children in Mode 3 to Mode 4, compared with Modes 1 and 2. This suggests an increase in Command and compliance behaviors in Cooperation-oriented modes between parents and children.

Negative interactions, which include "Verbal" and "Physical negative", as well as "Ignore" and "Non-compliance" behaviors, were generally infrequent. Children exhibited more negative behaviors, both verbally and physically, compared to parents overall. Both parents and children showed a higher frequency of "Negative behaviors" in Modes 1 and 4 compared to Modes 2 and 3.

Behaviors like "Questioning", "Reflecting", and making "Statement" were less frequent for both parents and children, and showed fluctuations across the four modes. Neither the parents nor the children showed any "Distraction" across the four game conditions.

The bar chart, shown in Fig. 9, presents the combined frequency of DPICS codes without separating sub-categories for parents and children, across the four game modes. "Command and compliance" appear at the highest frequency among all codes; they happened most often in Mode 3. "Positive affect" between parent and child is also high in frequency, with relatively consistent levels across all conditions. Negative interactions, including "Verbal" and "Physical negative", as well as the "Ignore" and "Non-compliance" behaviors, were generally infrequent and relatively lower in Modes 2 and 3. In addition, the results of the Friedman test revealed that there were significant differences across the four game modes for the "Question" behavior (p = 0.046 ¡ 0.05) and the "Command and Compliance" behavior (p = 0.041 ¡ 0.05). For other behaviors, no significant differences were observed across the four game modes.

Overall, the bar chart illustrates that positive and neutral interactions and dynamics were frequently observed between parent and child during gameplay in WonderFish.

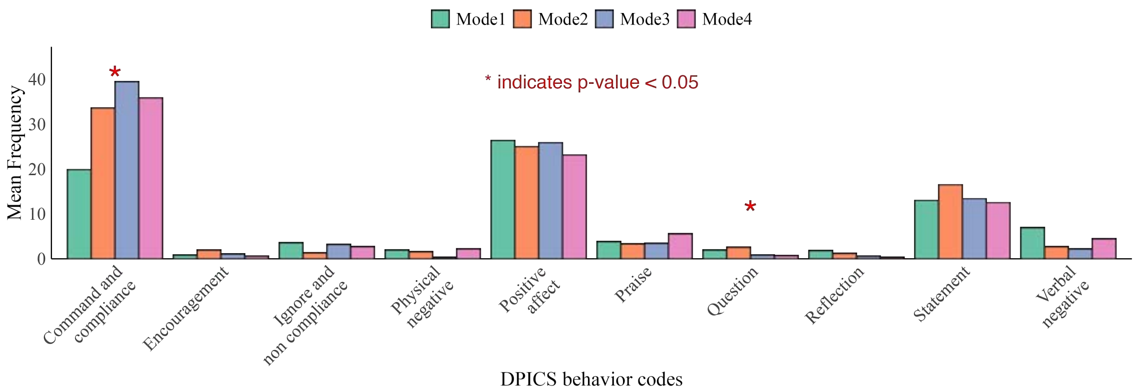

Figure 9: The visulized results on the main categories of DPICS codes

5.1.3 User Experience Analysis on questionnaires.

The analysis of children's survey scores across four modes reveals no significant differences, $\chi^2(3, N = 8) = 6.077$, $p = 0.108$. Descriptively, children's survey scores are highest in Mode 1 (M = 4.50, SD = 3.30) and lowest in Mode 4 (M = 2.25, SD = 0.7). Given the adapted two-item survey and the small sample size (N = 8), reliability estimates were unstable. Cronbach's α coefficients were 0.85 for Mode 1, 0.61 for Mode 2, –0.07 for Mode 3, and 1.00 for Mode 4.

Moreover, marginal significant differences are observed in parent-report survey scores across four modes, $\chi^2(3, N = 8) = 6.396$, $p = 0.094$, η^2= 0.267. Descriptive statistics indicated that parent-report scores are highest in Mode 3 (M = 19.38, SD = 1.06) and lowest in Mode 1 (M = 18.13, SD = 1.89). The adapted survey exhibited low to moderate reliability across the four experimental modes (Cronbach's α = 0.137 to 0.684), which is consistent with the reduced number of items.

5.2 Qualitative results

5.2.1 User Experience Analysis on Interviews

Given communication differences and executive function demands for some autistic children in interview settings, we primarily interviewed the parents from these eight groups to gather their perspectives on WonderFish. The amount of information collected was not extensive. All eight parents reported that their children enjoyed the game and exhibited higher levels of engagement compared to traditional physical activities. They also expressed a desire for future iterations to incorporate more physical activity to further enhance engagement and exercise. Two parents noted that the game became relatively easy for their children after practicing a few modes, which could lead to boredom and limit the effectiveness of this exergame as a daily intervention. Additionally, five parents suggested that offering diverse avatar options and different game environments — such as birds in the sky and robots in space — could enhance the user experience. These insights provide valuable guidance for the future development of WonderFish.

5.2.2 Within-subjects data visualization and analysis on physiological signals with parent-child interactions

The results of the quantitative analysis using repeated one-way ANOVA revealed that no significant differences were observed in HRV metrics between the game modes (p ¿ 0.05) due to the small sample size. Therefore, our qualitative analysis focused on the visualization of HRV data aligned with real-time game timestamps, annotated with details of parent-child interactions.

Figs. 10 to 17 visualize each parent-child dyad's RMSSD across the entire experiment, with the red line representing the child's RMSSD and the blue line representing the parent's. Colored shaded areas mark different game modes, while the gray areas indicate break periods during which participants could rest, review game results, and complete surveys. We also dived into behavioral and physiological changes between subjects under the same mode, as shown in Figs. 18 to 21, which display RMSSD changes for all eight dyads in each game mode.

This approach provides detailed insights into the changes within each dyad and also offers a broader picture of potential interaction and physiological patterns in the collective groups.

Group 1 The dyad started with **Mode 1**. Both the parent and the child primarily focused on the virtual avatar's movements, with the child tending to mimic the parent's actions in the virtual space rather than the physical environment. The mother offered guidance on physical motions, saying: "Use your waist to move left and right, but use your arm to move up and down," which the child followed.

In **Mode 4**, the dyad actively discussed how to coordinate their bodily interplay. The child observed the mother's physical movements and frequently gave her instructions. Although the mother tried to guide the child by tapping or positioning his shoulder, he found these physical interventions annoying. Overall, their interactions became more reciprocal and self-reflective, extending bodily collaboration further into the physical world.

Moving on to **Mode 2**, the child quickly grasped the turn-taking rules and mimicked his mother's virtual movements. The mother had more time to reinforce the child when she was not playing, while the child focused on observing the mother's avatar. In **Mode 3**, their conversation on how to collaborate actively continued, with the child providing numerous suggestions to his mother.

Overall, the dyad became more proficient at controlling the avatar through bodily motions, exhibiting lower stress and reduced tension in their interactions as the game progressed. Their RMSSD (see Fig. 10) initially fluctuated in the first two modes, but leveled off in **Modes 2 and 3**.

Group 2 As shown in Fig. 11, the child's RMSSD was higher than the parent's throughout the game, displaying greater variability and more pronounced fluctuations. In **Mode 3**, the dyadic RMSSD followed a similar trend, reflecting initial difficulties in coordinating movements. However, they improved their collaboration through simple requests to each other. For example, the child asked, "Mom, could you move up a bit?". In **Mode 1**,

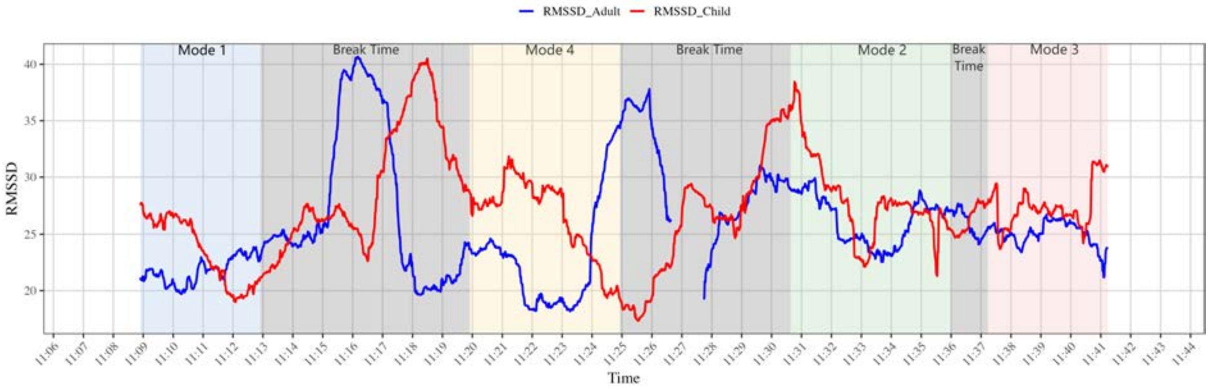

Figure 10: Group 1 Data Visualization: child's and parent's RMSSD during the entire WonderFish game

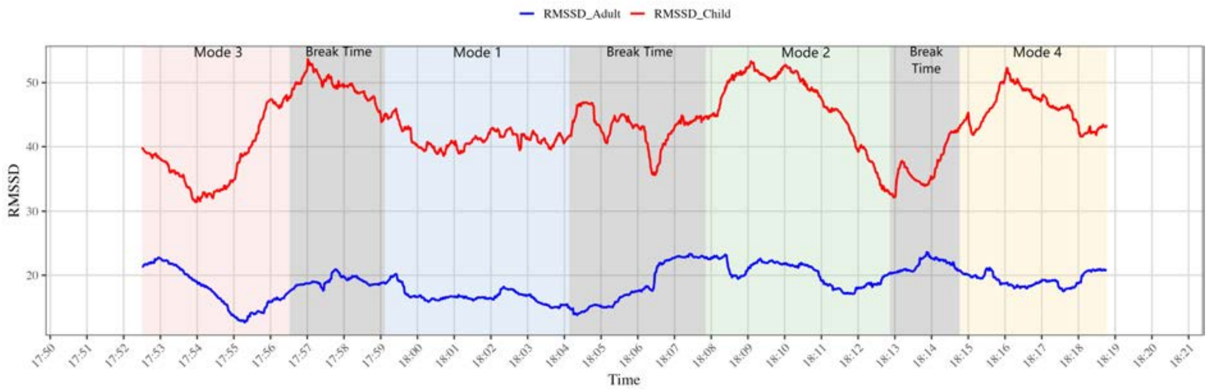

Figure 11: Group 2 Data Visualization: child's and parent's RMSSD during the entire WonderFish game

the pair had minimal interaction and focused primarily on collecting their own bubbles, which may explain the stable RMSSD in this mode.

The child generally managed turn-taking well, though he occasionally became distracted by the virtual environment while waiting for his turns in the turn-based modes. In **Mode 2**, the child frequently failed to collect bubbles on his turns, relying solely on his own movements without much intervention from his mother. This led to demoralization, coinciding with a significant decrease in his RMSSD. By contrast, **Mode 4** had a more collaborative nature, where the mother offered additional guidance and feedback on the child's movements to collect each bubble. This shift toward positive, cooperative interaction enhanced their game performance and correlated with an increase in the child's RMSSD.

Group 3 Overall, this dyad exhibited a passive interaction dynamic. The child frequently scrutinized the mother's movements and blamed her for missing bubbles. Toward the end of **Mode 3**, the child exclaimed, "Hate you!". The mother responded softly, "Please, don't blame me." This negative dynamic was reflected in the mother's decreased RMSSD at the end of Mode 3 (see Fig. 12).

In **Mode 1**, the dyad did not imitate each other's movements, instead focusing on their own performance with minimal interaction. By **Mode 2**, they took turns without any problem and guided each other when it was not their turn. In **Mode 4**, the mother struggled with positioning, leading the child to express frustration multiple times. The mother attempted to calm the child, saying, "Please don't get angry; I'm trying. . . ," but these negative interactions were reflected in her low-level RMSSD. Throughout **Mode 4**, the child unilaterally directed the mother's movements.

Group 4 This dyad exhibited relatively stable and synchronized RMSSD across all modes (see Fig. 13). The child demonstrated strong competency in handling the game, and their interactions remained positive throughout. The mother frequently offered compliments and encouragement, and both remained actively engaged across every

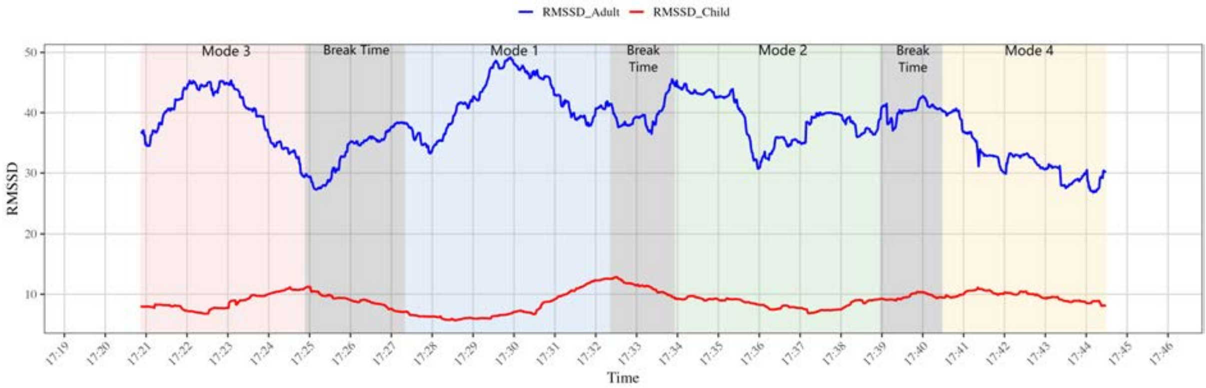

Figure 12: Group 3 Data Visualization: child's and parent's RMSSD during the entire WonderFish game

mode.

In **Mode 3**, he focused on his own movements yet occasionally reminded his mother to adjust hers. He also pointed out her mistakes and suggested improvements. In **Modes 4 and 2**, they experienced no difficulty taking turns. During the mother's turns, she demonstrated movements and shared tips for better performance; however, the child mainly watched the screen rather than her physical cues. The mother said, "Mode 4 is harder than Mode 2".

In **Mode 1**, the interaction dynamic became more relaxed, largely due to the mother's playful jokes. She repeatedly called the child a "naughty little fish," saying, "Why doesn't the naughty little fish follow me?" The child laughed and replied, "I'm not a naughty little fish, I'm a hardworking little fish." This lighthearted banter contributed to a higher RMSSD for both participants. However, a minor conflict arose when their two fish interfered with each other in the virtual environment.

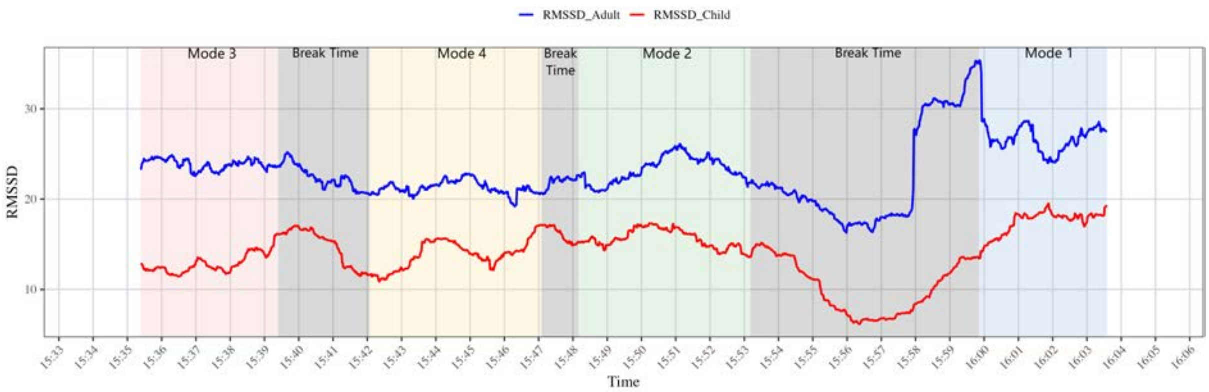

Figure 13: Group 4 Data Visualization: child's and parent's RMSSD during the entire WonderFish game

Group 5 This dyad collaborated effectively under the father's direction in **Mode 3**. At one point, when the father's RMSSD dipped in Mode 3 (see Fig. 14), the child blamed him for a failed attempt, shouting, "It's all your fault!" The father gently responded, "Don't blame me," and continued offering guidance. The child asked the parent to do specific motions, suggesting an emerging sense of collaboration. Later in **Mode 3**, when the child became frustrated with her body control, the father consoled her verbally.

In the turn-based modes, the child actively claimed her turns and sometimes instructed the father on his turns. Their interactions remained supportive and collaborative overall. In **Mode 2**, the child observed the father's body movements and tried to emulate them, while the father provided physical demonstrations to help her. Toward the end of this mode, the child grew frustrated when controlling her fish via body movements, possibly contributing to the drop in her RMSSD. At the start of **Mode 4**, the dyad struggled with coordinating their bodily interplay, but they engaged in active conversation to align their movements. Through continued effort, they collaborated smoothly in Mode 4, as reflected in the relatively stable RMSSD levels for both the child

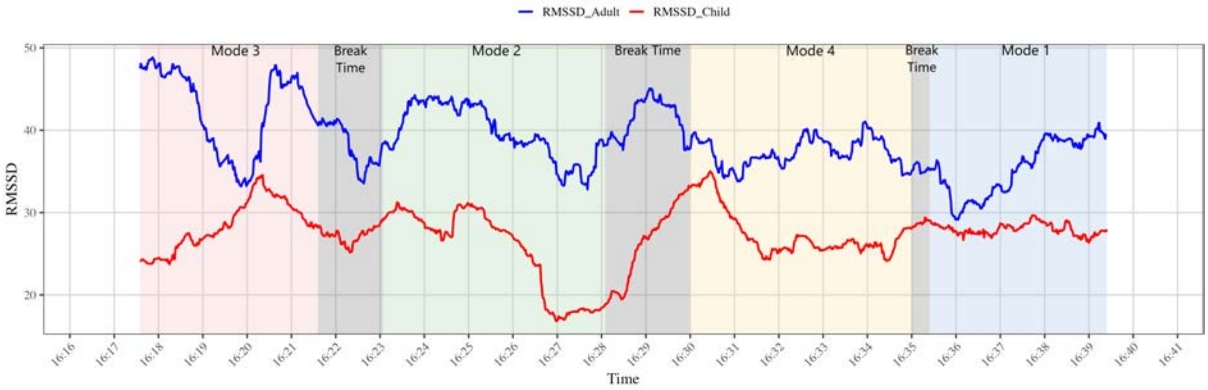

Figure 14: Group 5 Data Visualisation: child's and parent's RMSSD during the entire WonderFish game

and the father.

In **Mode 1**, they played mostly independently and occasionally clashed over physical space. Each focused on individual movements but still paid attention when the other collected bubbles.

Overall, the child displayed intense emotions. She often blamed her father for mistakes, while the father consistently attempted to calm her and provide steady support.

Group 6 This dyad maintained a calm and consistent dynamic across the four modes. In **Mode 4**, the child took turns and followed the parent's instructions. During **Mode 1**, they focused on learning the gameplay techniques and independently adjusting their body movements. By **Mode 2**, the child had grasped these techniques and performed most motions successfully during his turns. He also grew slightly distracted by the user interface and game environment when it was the parent's turn, at times asking questions like, "When can the fish swim to a different sea?" In **Mode 3**, after missing a few bubbles, the dyad discussed ways to improve their bodily interplay.

Overall, the dyad spent the first two modes primarily learning the fundamentals and syncing their movements. Once the child became proficient, especially by **Mode 2**, he appeared more relaxed. The change likely contributed to higher RMSSD levels for the child in the later game, as shown in Fig. 15.

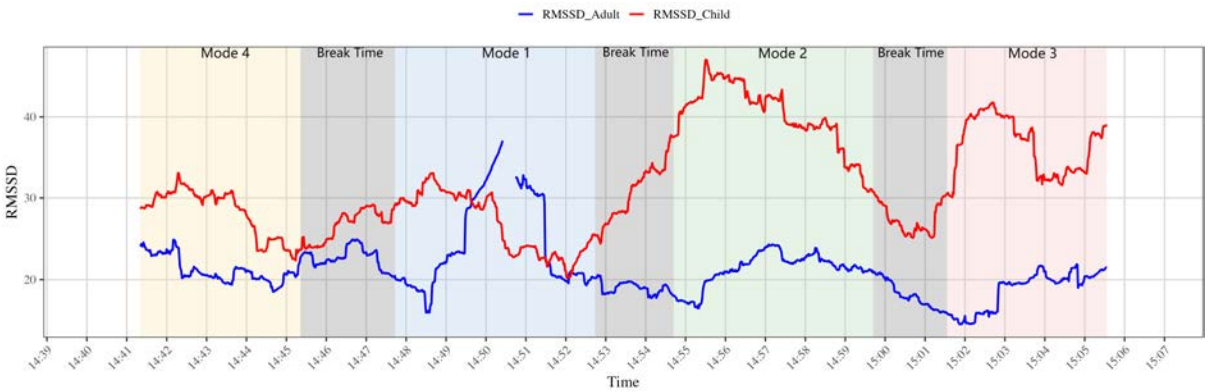

Figure 15: Group 6 Data Visualization: child's and parent's RMSSD during the entire WonderFish game

Group 7 This dyad started from **Mode 4**, where the child struggled to adjust his body movements to control the fish. He did not appear to fully grasp the rules and largely relied on his mother's directions. The child repeatedly complained: "Mom, this is so hard!" and kept calling out "Mom!" coinciding with a sharp drop in his RMSSD (As shown in Fig. 16).The mother demanded specific motions (e.g., "I told you to move your upper body left and right!") and showed signs of impatience when the child failed to follow through. Later in **Mode 4**, she modified her approach by combining verbal instructions with gestures, which brought some positive interactions with a lot of relaxing moments that resonated with a significant rise in their dyadic RMSSD.

Moving on to **Mode 2**, the mother was notably more patient. She normalized mistakes, offered physical demonstrations of how to perform certain motions, and generally interacted in a more positive manner. The child initiated turn-taking behaviors, managing turns more effectively than in **Mode 4**. This improvement was reflected in relatively stable dyadic RMSSD data, and the child's RMSSD reached its highest levels among all modes.

In **Mode 3**, the interaction dynamic shifted again as the child began guiding his mother. He frequently directed her with comments like "This way, a bit up!" and "Turn left!", displaying a cooperative mindset by monitoring her movements rather than focusing solely on the screen. The dyad's movements matched well, and their RMSSD fluctuations also synchronized closely.

During **Mode 1**, the child fell into a paranoid ideation and became fixated on the idea that he had missed a bubble, while the mother thought he had successfully collected it. Although they continued playing, the child repeatedly revisited this perceived mistake and grew frustrated, and he said his mother would not concede. He even threatened, "If you lie to me, I will poke the bubble on your side," but the mother reacted calmly and laughed it off. This incident appeared to increase the child's stress, which brought a big cut on child's RMSSD.

Overall, the mother actively provided instructions but offered few compliments for the child's successes. Nevertheless, the child's movement skills and performance improved throughout the game, and he often initiated collaborative behaviors with his mother. Their interaction evolved over time, punctuated by intense moments, as seen in Mode 1.

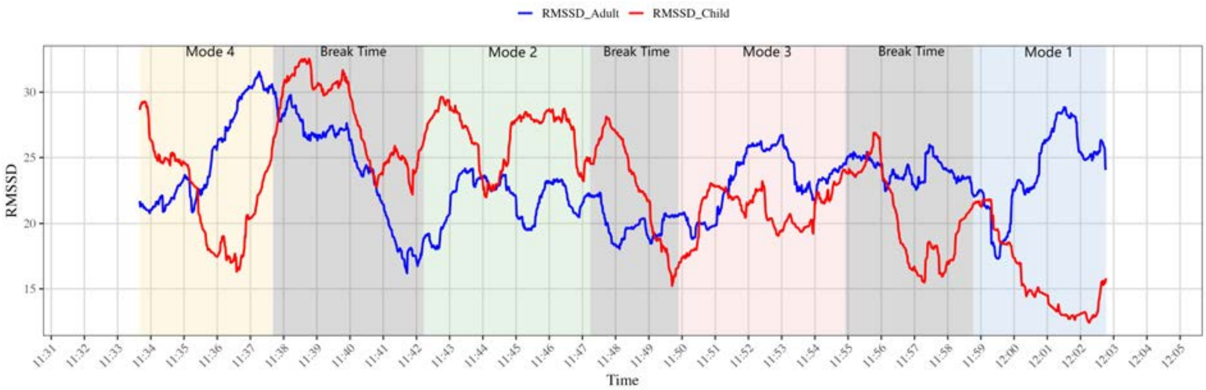

Figure 16: Group 7 Data Visualization: child's and parent's RMSSD during the entire WonderFish game

Group 8 The overall interaction dynamic during entire game was very positive and encouraging. Both the parent and the child were fully engaged in WonderFish and showed no signs of distraction. The father provided a lot of encouragement and positive reinforcement, and he also offered verbal guidance to help his child with the required motions, making a considerable effort to keep the collaboration.

Fig. 17 presents the HRV data visualization for Group 8 in the progress of four modes. Throughout the game, the child's RMSSD remained consistent and varied less than the parent's.

In **Mode 4**, the father frequently indicated whose turn it was, but the child sometimes acted during the father's turn. Although the child generally followed his father's guidance, the dyad performed less effectively than they did in **Mode 2** in terms of both game outcomes and interactive dynamics. The child said "Missed" two times when they failed in collecting bubbles. By contrast, in **Mode 2**, the pair displayed more excitement and engagement, reflected by a higher peak RMSSD for the parent. The child also spoke and asked questions more frequently, saying things like "It should be fine now!"; "It is my turn!"; "What is the problem?"; and "What is it?" The child did not always take turns correctly, which sometimes conflicted with the father's actions in both **Modes 2** and **4**.

At the beginning of **Mode 1**, the dyad missed several bubbles. The father pointed out these mistakes, for example saying, "We missed it — you should've moved to the right side!" Once they caught on to the gameplay techniques, their motions became highly synchronized. Later in this mode, the child was very happy and excited whenever they hit a bubble, and he even jumped up to celebrate. This shift is also visible in the parent's RMSSD data: it started off relatively low, likely due to initial stress, and then gradually rose as their performance improved and they became more relaxed.

A similar pattern emerged in **Mode 3**. The child struggled initially, and the father showed signs of stress as he attempted to correct the child's motions, indicated by his low RMSSD. However, as they progressed, their collaboration improved, they collected more bubbles, and the father's RMSSD rose accordingly.

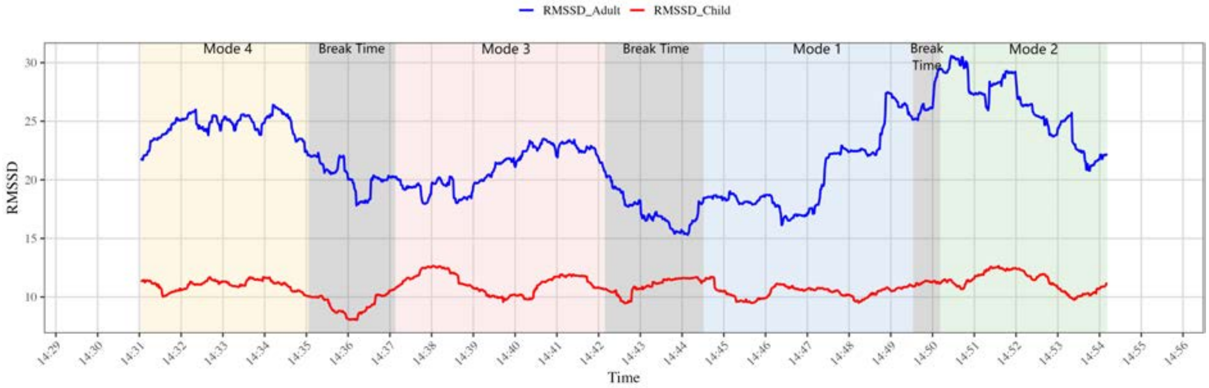

Figure 17: Group 8 Data Visualization: child's and parent's RMSSD during the entire WonderFish game

5.2.3 Between-subjects data visualization and analysis on physiological signals with parent-child interactions

Overview of RMSSD of Eight Groups in Mode 1 In this mode, dyadic interactions in the physical world were limited. Both parents and children primarily concentrated on their own movements and devoted most of their attention to the on-screen virtual world. Parents occasionally offered verbal guidance, while children often mimicked the movements of the parent's avatar.

In the virtual space, Groups 5, 7, and 8 encountered conflicts when their fish avatars blocked each other from collecting bubbles, prompting discussions about territorial claims in the virtual space. As shown in Fig. 18, the children's RMSSD remained relatively steady, reflecting their calm autonomic nervous activity due to limited in-person interaction. By contrast, the parents' more fluctuating RMSSD aligned with their efforts to multitask, not only maintain their own game performance but also support their children's performance.

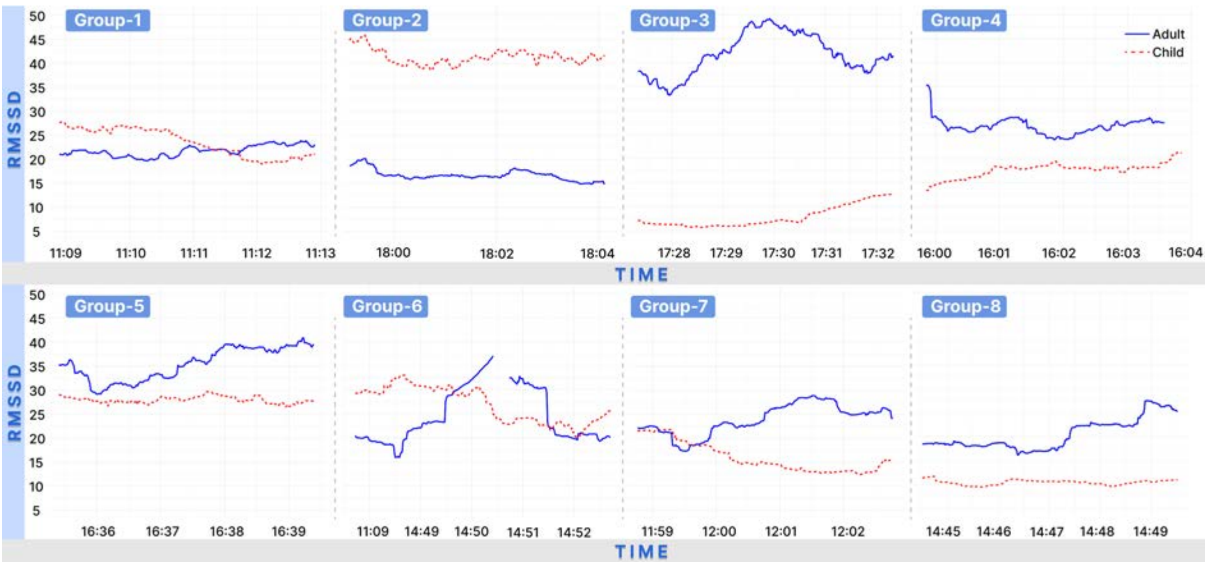

Figure 18: Physiological Data Visualization on RMSSD of Eight Groups in Mode 1

Overview of RMSSD of Eight Groups in Mode 2 Most children understood and followed the turn-taking rules in Mode 2. They had time to observe both their parents' body movements and the avatars' motions, and they offered instructions to their parents. Meanwhile, parents used the time between turns to help guide their children's body movements, resulting in more structured and active interactions in both the physical and virtual worlds. Compared with Mode 1, these interactions were more reciprocal rather than unilateral.

The dyadic RMSSD also tended to synchronize well in Fig. 19, especially among Groups 1, 4, 5, and 7, indicating an interpersonal influence on physiological responses. Moreover, parents' RMSSD values were less variable and notably higher than those in Mode 1, suggesting a calmer, less stressful state for the parents.

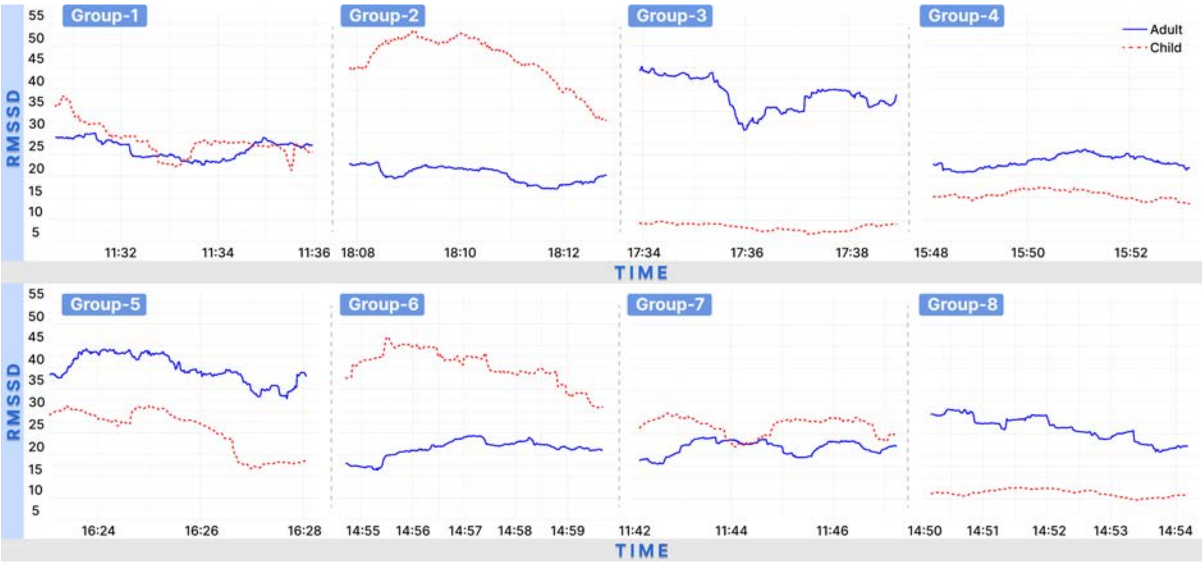

Figure 19: Physiological Data Visualization on RMSSD of Eight Groups in Mode 2

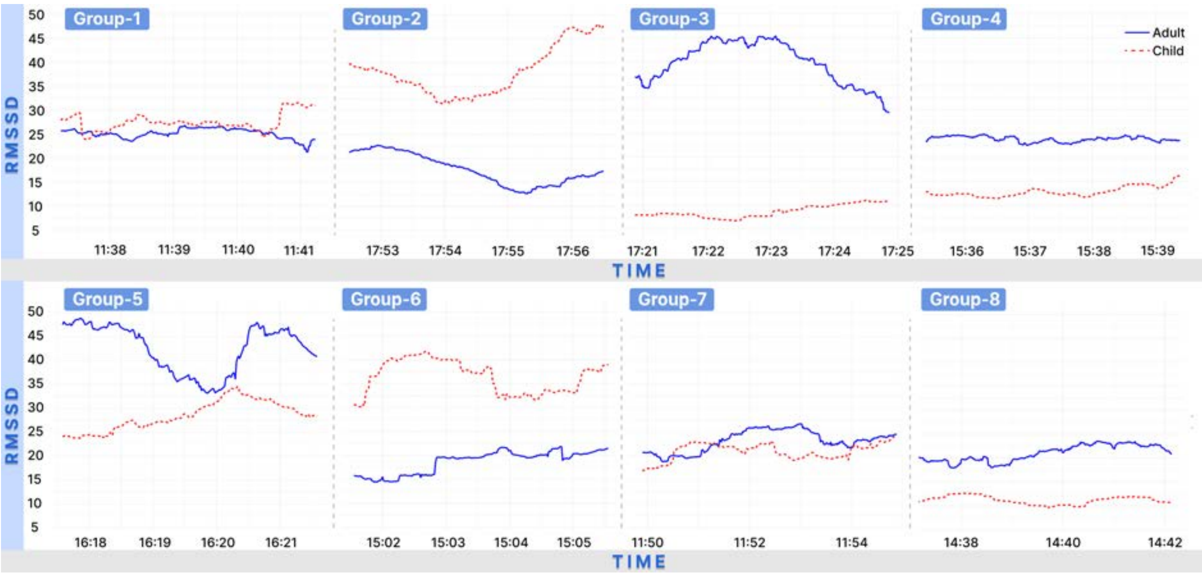

Figure 20: Physiological Data Visualization on RMSSD of Eight Groups in Mode 3

Overview of RMSSD of Eight Groups in Mode 3 Due to the collaborative nature of Mode 3, the dyadic interactions were more active for all groups. However, it was more intense for some groups due to negative interactions. For example, the children in Groups 3 and 5 blamed their parents for missing bubbles. Each dyad had a shared body in the virtual world, which led to more interventions between participants in the physical world. Conversely, these successful bodily collaborations fostered more positive interactions. Consequently, as shown in Fig. 20, these varied dynamics are reflected in distinct RMSSD patterns across the different dyads.

Overview of RMSSD for the Eight Groups in Mode 4 In this mode, dyadic interactions remained active, observed with verbal prompts and physical interventions from both children and parents. The inherent parent-child interaction dynamic did not change significantly for each group compared to Mode 3; for example, similar negative interactions continued to surface in Groups 3 and 5. The turn-taking rule afforded both parents and children additional time to interact while alleviating the stress of continuous body movements. This shift may explain the smoother variation in both parents' and children's RMSSD values (see Fig. 21) in Mode 4 compared to modes without turn-taking.

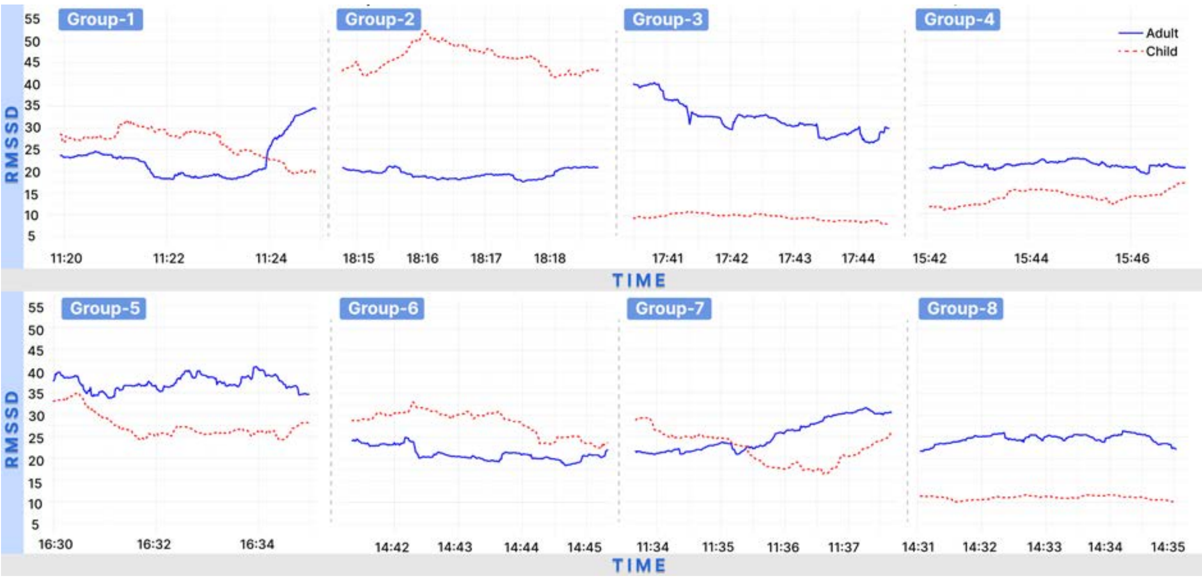

Figure 21: Physiological Data Visualization on RMSSD of Eight Groups in Mode 4

6 DISCUSSION

Due to the explorative nature of our work, we draw on both quantitative and qualitative results to discuss insights related to our three research questions rather than offer definitive answers. We also acknowledge several study limitations and provide design implications for future research.

6.1 RQ1: *"Can each game mode effectively train its targeted motor and social skills of children with ASD?"*

WonderFish is designed to integrate both behavioral and cognitive strategies to enhance social competence in children with ASD. Each of the four game modes targets specific motor and social skills: **Mode 1** concentrates on synchronized movements with parents and imitation skills for children with ASD, **Mode 2** focuses on developing turn-taking and imitation, **Mode 3** emphasizes cooperative matching movements, and **Mode 4** targets both turn-taking and cooperative skills. The results indicate that the game mechanics elicited the targeted motor and social behaviours and provided opportunities to practise them during parent–child collaboration across the different modes.

According to our behavioral coding, the highest frequency of "Imitation" occurred in **Mode 1**, where children primarily imitated the movements of their parents' avatars in the virtual world. In **Mode 2**, some children shifted their attention between the virtual environment and their parents' physical movements between turns, and appeared to mimic parents' movements. In both **Mode 1** and **2**, children also imitated motions based on their parents' verbal prompts.

For cooperative behaviors, we assessed whether children performed movements to match their parents' for controlling the fish in the virtual world. Most children learned these matching movements through cues on the game interface and parental instructions, although a few experienced difficulty coordinating their bodies—particularly in **Modes 3** and **4** — and struggled with one-direction movements. Still, we witnessed a growing sense of collaboration and reciprocal behaviors in these two modes, such as children supporting their parents with body coordination. The shift toward the shared body (one fish avatar), and the shared object (collecting bubbles) in the virtual world contributed to changes in children with ASD and encouraged their in-person collaboration [Mueller et al.(2017)].

Regarding turn-taking skills, not all child participants grasped turn-taking rules and sometimes acted during their parents' turns. However, most adapted to turn-taking through parental guidance. Notably, Mode 4 elicited more turn-taking behavior than Mode 2, possibly because its higher level of bodily interplay in mixed reality fosters collaborative competencies, including turn-taking [Mueller et al.(2017), Huang et al.(2022)].

Although children with ASD often face challenges in comprehending social norms, rules, and constructs [Nah and Poon(2011)], and may struggle with fully grasping the social implications of collaboration [Bauminger-Zviely et al.(2013)], our exploration with WonderFish indicates that children with ASD can exhibit various collaborative behaviors, including imitation, cooperation and turn-taking, across four game modes. These behaviors reveal their emerging understanding of collaboration for achieving micro goals, such as collecting bubbles, in the exergame.

However, given the single-session, small-simple study, our findings speak to elicitation and short-term practice opportunities, not to clinical change, longitudinal studies are needed to evaluate skill acquisition and transfer.

6.2 RQ2: *"How does each game mode impact social interactions between children with ASD and their parents? "*

Recent collaborative play work with autistic children [Hijab et al.(2025)] demonstrated the importance of joint engagement as an evaluation lens, they explicitly codes **Turn Taking** and **Joint Attention** during play sessions to characterise collaboration and track shifts from solitary or parallel to collaborative activity. We adopt the same lens to interpret our behavioural findings with examining transitions across game modes to quantify how mode structure and mechanic "dials" influence collaborative interactions in dyads.

Observational data enabled us to analyze behavioral interactions within each dyad, which were further validated in their physiological responses. As elaborated in the paragraph titled *Overview of RMSSD of Eight Groups in Mode 1*, the parallel-play setting led both children and parents to focus primarily on their own movements, resulting in fewer bilateral interactions compared to other modes. We also witnessed an increase in negative verbal instructions from parents to children during **Mode 1**.

In **Mode 2**, introducing a turn-taking rule to parallel play encouraged dyadic interactions. While body activity remained parallel, the level of reciprocity in parent-child communication increased. For example, both parents and children provided feedback on body movements during each other's turns. Prior HCI works have highlighted the importance of such reciprocity norms for fostering social skills in children with ASD [Hong et al.(2012), Shin et al.(2021)] and maintaining a good parent-child relationship [Shin et al.(2021)].

Mode 3 was designed to promote a high degree of bodily interplay by creating a shared space (the sea world), a shared object (collecting bubbles), and a shared body (one fish avatar) [Mueller et al.(2017)] in mixed reality. We witnessed successful bodily collaborations in this mode, often leading to positive interactions, but failures triggered conflicts in parent-child dyads. For instance, some children blamed their parents for missed bubbles—even when the child was responsible. These varied social dynamics were reflected in distinct physiological patterns: while some dyads exhibited synchronized RMSSD trends, others — such as Group 5 — displayed opposite patterns. The similar social dynamics continued in **Mode 4**, but the turn-taking rule reduced both overall gaming stress and collaborative tension, as evidenced by the smoother RMSSD variations shown in Fig. 21, compared to Mode 3.

Prior exergame work [Saksono et al.(2015)] has emphasized collaborative effort in family-focused exergames to foster positive social interactions in parent-child dyads. However, the different forms of bodily interplay in WonderFish distinctly fostered both positive and negative interactions in parent-child dyads. Although the relationship or intrinsic interaction dynamic in dyads might influence their interactions in the exergaming experience [Park et al.(2012)], our findings still challenge the HCI communities to reconsider how to design computer-supported collaborations that influence social dynamics between children with ASD and non-autistic individuals.

6.3 RQ3: *"What are the perceptions of the user experience with WonderFish among children with ASD and their caregivers? "*

Although the survey results from both children and parents indicated no significant differences across the four modes, a notable discrepancy arose in user experience: children enjoyed Mode 1 more than the other modes, whereas parents perceived Mode 1 to be their children's least preferred. This mismatch in perceptions was clarified through an analysis of observational data and interview feedback. Parents believed the children were most engaged in Mode 3, pointing to their active responses and interactions. Meanwhile, parents reported the children had minimal engagement in Mode 1 since they displayed little response and played more independently. Conversely, children favored Mode 1 because it was easier and required less reliance on their parent, whereas they enjoyed Mode 4 less due to the higher demands of varied body movements and increased dependence on parents.

Such contrasting perspectives may stem from differing social play tendencies between neurotypical and neurodivergent individuals [Morris et al.(2024)], especially considering interpersonal barriers associated with autistic traits [Ghanouni et al.(2019)]. Indeed, research shows that children with ASD have a strong preference for solitary play and exhibit repetitive play patterns [Jarrold(2003)].

With the goal of enhancing both motor and social skills in children with ASD, while acknowledging their unique preferences for promoting long-term engagement, we suggest that social exergame designs incorporate the diverse play categories [Parten(1932)], including solitary and onlooker play, and progress in social complexity to parallel play, associative play, and the most intricate form, cooperative play. This approach aligns with the most recent HCI research by Morris et al. [Morris et al.(2024)], who propose connecting autistic children in social play by assigning them parallel play under the same theme as their play partners.

Overall, children remained notably focused and fully engaged throughout the exergame, which is significant given that prolonged attention can be effortful for many autistic children, especially during tasks involving complex social interactions [Ghanouni et al.(2019)]. Parents appreciated the engagement of physical exercise through the mixed reality experience but expressed concerns about the limited variety of motion patterns, as well as the restricted modes and levels. Some children experienced overly tight timing/precision requirements or dense visual fields, while others found repeated targets/themes too predictable. These perceptions aligned with observations and telemetry (e.g., relatively high SD in success rate). In response, we emphasize the importance of designing for the heterogeneity of autism within technology-facilitated interventions [Graham et al.(2022)]. Specifically, exergames should include varying levels of bodily interplay and intensities of motion to accommodate a broader range of social and motor abilities across the autism spectrum.

6.4 Study Limitations and Future work

This study has several limitations that require discussion. First, our sample size was relatively small, comprising only eight parent-child pairs, which may have limited the statistical power of our findings and contributed to the absence of significant differences, especially in HRV data. A larger sample size could yield a more precise understanding of how HRV reflects responses to intervention stimuli and social interactions among children with ASD. Furthermore, our child participants were mostly males from a relatively homogeneous cultural background, potentially constraining the generalizability of our results. The accompanying caregiver was predominantly the mother, which may shape both interaction dynamics and proxy reports (e.g., parental perceptions of engagement). The effectiveness of WonderFish across diverse cultural and age groups with balanced gender representation remains unverified and requires further exploration. Therefore, future studies should aim to recruit a larger and more diverse sample to enhance the representativeness and statistical robustness, which may reveal more distinct patterns in physiological and behavioral responses.

Moreover, data were collected at a single site, raising the possibility of a novelty effect, influencing observed behaviors [Tsay et al.(2020)]. Repeated exergaming sessions in a longitudinal study could provide deeper insights into the game's effects on motor and social skills of children with ASD. Future research employing a longitudinal design will be essential to validate game effects over time and to assess the intervention in promoting long-term engagement.

Our current build uses fixed parameters, which limits fit across diverse profiles and day-to-day fluctuations.

In future iterations, we will implement adaptive mechanics that calibrate difficulty at session start (e.g., brief baseline to set initial target size/speed and cue strength), and personalise across sessions (e.g., staircase on recent success rate; enlarge targets after consecutive misses; tighten only after sustained success).

To align with neurodiversity-affirming practice, further design iterations of WonderFish are necessary to enhance user experience from a co-design stance, using play sessions to surface requirements and tune difficulty and feedback in situ [Hijab et al.(2025)]. For co-designing collaborative play with autistic children, we can incorporate features such as varied avatars and virtual environments in users' options [Hijab et al.(2024)]. One suggestion that emerged from interviews with parents — designing robot avatars in space reality — may be overly abstract for some children with ASD. Future design should prioritise the preferences of autistic children like more concrete, familiar schemas and scaffolded introductions (icons, demos, storyboards) to ensure comprehensibility and reduce cognitive load [Malinverni et al.(2017)]. For mixed-reality exergames, UX elements and interactions should be matched to children's cognitive traits [Khowaja et al.(2021)], with predictable mappings (one action = one effect), limited visual density, and gradual complexity [Malinverni et al.(2017)]. The recent inclusive co-design with autistic children review [Hijab et al.(2024)] suggested that positioning children and parents as partners to calibrate elements of the mixed reality platform, such as avatars, effects and sounds, to users' sensory preferences. To further enhance engagement and adherence, we can explore AI-powered personalisation which enables children (with caregiver oversight) to generate preferred avatars and virtual environments across sessions [Paneru and Paneru(2024)].

Finally, physiological signals (e.g., HR/HRV) should not serve as primary measures of social interaction in movement-rich exergames since these signals are confounded by movement, respiration, and exertion [Qiu et al.(2024), Qiu et al.(2021)]. Future work on socially assistive systems should treat physiology as contextual while foregrounding gaze-based engagement [Qiu et al.(2021)] and joint-engagement coding [Hijab et al.(2025)], and should include explicit exertion controls (e.g., accelerometry) [Qiu et al.(2023)] to disambiguate sources of change.

7 Conclusion

In this study, we explored how to incorporate bodily interplay theory in mixed reality to enhance the motor and social skills of children with ASD. We began by extending existing bodily interplay dimensions and adapting them into foundational game mechanisms for our target user group. Building on these dimensions, we created WonderFish, an exergame featuring four distinct game modes that facilitate different forms of collaboration between children with ASD and their parents. We detailed the design process and components of the WonderFish prototype, then conducted experiments with eight user groups to evaluate WonderFish in terms of our three primary research questions. We employed a comprehensive data analysis approach that integrated behavioral and physiological measurements, as well as both objective and subjective assessments. Through this empirical investigation, we gained in-depth insights into how various forms of computer-supported collaboration shape the interaction dynamics between children with ASD and their parents. Rather than demonstrating clinical improvement, our findings offer HCI communities an innovative socially assistive design and outline design implications for leveraging mixed reality to elicit targeted motor and social behaviours within parent– autistic child collaboration.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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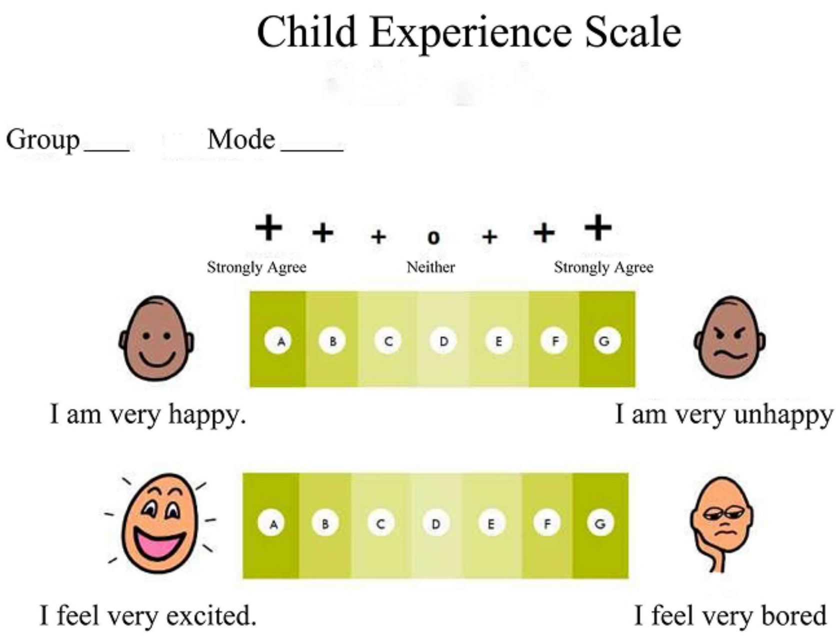
A Appendices

A.1 Appendix 1: Child Experience Scale



A.2 Appendix 2:Parent-report Survey

Physical Game Mode Experience Questionnaire

This questionnaire is primarily for parents to complete, assessing the child's game experience. It should be completed after each game mode.

1. Group Number [Fill in]

____

2. Game Mode

○Mode 1

○Mode 2

○Mode 3

○Mode 4

○Special Case ________________

Questions to be completed by parents

3. How would you rate your overall impression of our system?

Very Dissatisfid	○1	○2	○3	○4	○5	Very Satisfied

4. How would you rate your child's level of attention?

Low	○1	○2	○3	○4	○5	High

5. How would you rate your child's level of engagement?

Low	○1	○2	○3	○4	○5	High

6. How would you rate your child's task completion?

Very Dissatisfid	○1	○2	○3	○4	○5	Very Satisfied

7. How would you rate your child's emotional state?

Low	○1	○2	○3	○4	○5	High

8. How would you rate your child's understanding of the game rules?

Easy to Understand	○1	○2	○3	○4	○5	Hard to Understand

A.3 Appendix 3:Interview Questions

After the WonderFish experiment, we conducted a semi-structured interview with the parent-child dyad to explore their user experience. The interview focused on six core questions:

1. What aspects of WonderFish do you like and dislike, and why?
2. Which game mode do you prefer or like less, and why?
3. How do you and your child usually engage in physical or collaborative activities?
4. Compared to your (your child's) physical and collaborative activities, what advantages does WonderFish offer—or what might it be missing?
5. Do you have any suggestions for improvement?
6. If you were to design an exergame for yourself and your child (parent), how would you approach it?

Based on individual's responses, the researchers asked additional follow-up questions to delve deeper into relevant topics.

A.4 Appendix 4:Behavior Coding Scheme

Table 6: Behavior Coding Scheme

Code	Definition	Coding Criteria	Examples
Imitation	The child actively or passively imitates the physical action of their partner or the movements of the parent's avatar (fish) in the virtual environment.	- The child observes and mimics the same physical bodily action of the parent. - The child controls their avatar to the same direction as the parent's avatar goes. - The child's imitative action is initiated either spontaneously or in response to verbal cues from the parent.	- The parent's fish swims to the right to collect a bubble, and then the child follows the parent to control their fish and moves in the same direction. - The child checks and observes the physical bodily action of their parent and mimics a similar motion. - The child acts after hearing the instruction, such as "Follow me, turn left" from their parent.
Cooperation	The child engages in shared control of a single avatar (fish) with the parent, aiming to reach a joint goal (e.g., collecting bubbles), while showing bodily coordination or reciprocal actions.	- The child performs a matching movement in the opposite direction of the parent's (complementary actions), to collaboratively control the shared avatar in the virtual environment. - The child initiates the complementary actions either independently or in response to the parent's instructions. - The child requests collaborative actions from the parent.	- The child moves left or right while the parent moves up or down, coordinating to control the fish and collect bubbles. - In turn-based modes, the child performs complimentary movements to help control the fish. -The child guides the parent's actions to achieve the goal. For example, by saying: "Mom, go left."
Turn-taking	A structured alternation in which the parent and child take turns controlling the avatar (fish), demonstrating awareness of turn-taking through the child's actions or verbal cues.	- The child demonstrates an awareness of the turn-taking rule, through their actions or verbal cues. - The child engages in turn-taking with guidance from the parent.	- The child begins moving after (observing) the parent's actions. - The child stops moving during the parent's turn. - The child reminds the parent by saying "It's your turn". - The child initiates their movements following the parent' s prompt, for example: "You can take over now".