The Role of Partial Automation in Increasing the Accessibility of Digital Games

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Digital games are designed to be controlled using hardware devices such as gamepads, keyboards, and cameras. Some device inputs may be inaccessible to players with motor impairments, rendering them unable to play. Games and devices can be adapted to enable play, but for some players these adaptations may not go far enough. Games may require inputs that some players cannot provide with any device. To address this problem, we introduce *partial automation*, an accessibility technique that delegates control of inaccessible game inputs to an AI partner. Partial automation complements and builds on other approaches to improving games' accessibility, including universal design, player balancing, and interface adaptation. We have demonstrated partial automation in two games for the rehabilitation of spinal cord injury. Six study participants with vastly different motor abilities were able to play both games. Participants liked the increased personalization that partial automation affords, although some participants were confused by aspects of the AI's behaviour.

CCS Concepts: • **Human-centered computing → Accessibility technologies**; • **Applied computing → Computer games**.

Additional Key Words and Phrases: Game accessibility, personalization, automation, shared control, artificial intelligence

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1 INTRODUCTION

Numerous techniques exist for increasing the accessibility of games to persons with motor disabilities [101]. For example *Liberi*, an exergame designed for children with cerebral palsy, provides a simple control scheme that compensates for deficits in manual ability [50, 51]. *Wheelchair Revolution* provides an alternative interface that substitutes movement of a wheelchair for dance steps [39]. And *Gekku Aim* improves a player's aim by directly targeting the closest enemy when the player fires a shot [53].

Each of these approaches extends the range of people who can play, either by simplifying the interface, providing an alternative interface, or assisting the player in using the interface. However,

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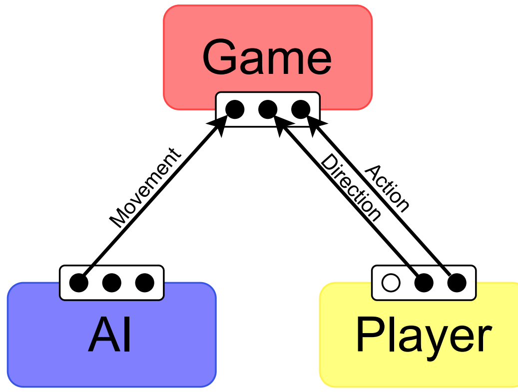

Fig. 1. Partial automation: The game interface offers inputs for controlling movement, direction, and game actions. The player controls as many of these inputs as they can (in this example, Action and Direction). An AI agent provides inputs for parts of the interface that the player cannot control (in this example, Movement).

these approaches are ultimately limited to people who can physically manipulate the interface's controls. For example, a person with complete paralysis due to spinal cord injury might be unable to control a joystick, and therefore would be unable to play any of these games [19, 31]. If part of a game's interface is inaccessible to a player, then they are disabled by the game and unable to play.

To address this problem, we introduce *partial automation*, a technique designed to complement existing accessibility techniques. With partial automation, the player controls those parts of the game's interface that they can use, while an artificially intelligent partner controls the rest of the game. For example, in a racing game, a person with complete paralysis might control the car's acceleration with a bite switch, while the AI partner steers the car. Partial automation is intended as a solution when other approaches such as alternative interfaces and game balancing are insufficient to make the game accessible. Specifically, partial automation serves as a last resort for making games accessible when other methods fail.

This paper contributes the first systematic characterization of partial automation and its role in making games accessible. Partial automation is illustrated in two digital games and evaluation by six persons with spinal cord injury. We ground our approach in the relevant shared control literature and introduce a novel ontology of accessibility approaches for digital games showing how partial automation relates to and complements existing techniques. An in-hospital study demonstrates that partial automation can make games accessible to players with radically different physical abilities. We contribute insights into how partial automation can affect experiences of play, identifying features that improved participants' experiences or caused confusion or disappointment.

The paper is organized as follows. We first introduce partial automation. We then review techniques for increasing the accessibility of games to people with motor deficits, showing how partial automation complements these approaches. We present the *Dino Dash* action game and the *Dozo Quest* platformer game as examples of the use of partial automation. Finally, we report on our study of these games with persons with spinal cord injury.

2 PARTIAL AUTOMATION

The core idea of partial automation is simple: a player controls those parts of a game's interface that they can, and an artificially intelligent agent controls those parts of the interface that the player cannot. Figure 1 shows an application of partial automation where the player provides

Table 1. Four games, representing different genres, and the devices players use to control their player-character's movement, direction, and action inputs.

Games	Movement	Direction	Action
Fortnite [33] (FPS)	Left analog stick	Right analog stick	Buttons & triggers
League of Legends [34] (MOBA)	Mouse and right click	Mouse	Keys
Mario Kart 8 Deluxe [22] (Racing)	A Button	Left analog stick	Triggers
Liberi [50, 51] (Exergame)	Pedal	Left analog stick	Buttons

Direction and Action inputs, while the AI is responsible for Movement. The game provides an interface controlled via some set of input devices, such as buttons or joysticks. These inputs correspond to game inputs that control different mechanics, such as setting the avatar's speed of movement, direction of movement, or performing actions such as jumping or shooting. If, for example, direction of movement of a player's avatar is specified using a joystick, players who can use a joystick provide that input themselves. For players who cannot use a joystick, the AI agent instead provides movement inputs to the game.

Under partial automation, players share control of their avatar with an AI partner. Any AI algorithm, or collection of algorithms, can be used for this purpose, so long as the agent can control any combination of the game's inputs. This allows players to engage in games even when they can't control all aspects of play, and to personalize the interface to whatever hardware they can use. Players must be able to control at least one game input, as otherwise gameplay would be completely passive.

We based our version of partial automation around three key input types of *movement, direction*, and *action* as these are the inputs underlying many existing types of games. As shown in Table 1, action games across multiple genres separate control of the player-character's activities into three types of game input controlled with different hardware. In *Fortnite*, for example, players use the left analog stick to move their character, while the right analog stick specifies direction of movement. Using partial automation, a player who can control at most one analog stick could choose to control either their character's movement speed or aiming direction while their AI partner controls the other input.

The split of inputs shown in Figure 1 into Movement, Direction and Action applies to a broad range of games including most avatar-based games such as Fortnite, League of Legends and Mario Kart, despite the very different control schemes used by these games. Other games might have different sets of inputs. For example, in the Real-Time Strategy game *StarCraft* [25], the inputs used to move a unit include *Selection* of the unit and *Targeting* of a desired location. Partial automation's input model and the AI underlying the player's AI partner may therefore need to be customized to the game.

We advocate the pairing of partial automation with other game accessibility techniques. For example, it is better to replace an input device with one that a player can use than to automate that input. But when these techniques fail—the player cannot use the device at all and there is no accessible alternative available—partial automation should be used. In the next section, we describe other approaches to making interactive systems accessible to users with motor impairments and discuss how partial automation can complement and extend the assistance they provide.

3 BACKGROUND

Designers typically limit a game's target audience to players with specific abilities, such as the ability to use a mouse and keyboard or the ability to use a gamepad controller. To extend a game's accessibility to those outside this target group, designers may need to create multiple versions of the same game or design support for multiple input devices. However, this may be costly when designing for small populations with uncommon abilities, such as players restricted to using a one-handed controller or a mouth-controlled device. The time and expertise necessary to support many input modalities may force developers to prioritize the needs of some players over others.

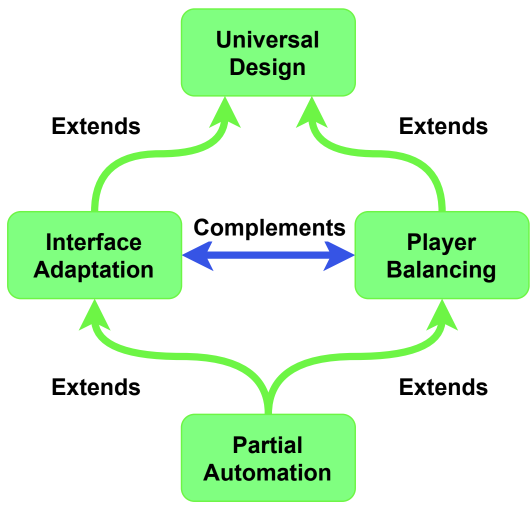

Fig. 2. The relationships among approaches to making games accessible to players with motor impairments. Interface adaptation and player balancing are complementary and can each be used to extend access to games that adhere to universal design. When used in conjunction with these other approaches, partial automation can extend access beyond their capabilities.

Several broad approaches, depicted in Figure 2, have evolved for improving the accessibility of games. Game designs can adhere to the principles of *universal design*, requiring only abilities held by the entire target audience. Games can also be made more accessible through *interface adaptation*, either through alternative interfaces designed for players with similar abilities, or through personalization of interfaces to the abilities of individual players. Additionally, players for whom controlling the game is too difficult can be assisted using *player balancing* techniques that adjust the difficulty of the game's challenges. Partial automation can be used in conjunction with each of these approaches, or any combination of them. When making serious games (such as rehabilitation games) more accessible using any of these approaches, designers need to avoid "designing away" aspects of the game that are essential for its serious purpose. For example, a rehabilitation game might improve arm strength through the use of an arm ergometer as an input device [29]; allowing the arm ergometer to be replaced by a joystick might improve accessibility, but at the unacceptable cost of removing the arm exercise from the game.

In this section, we provide an overview of these approaches and their application to accessibility of games for players with motor impairments. We then illustrate how they can be complemented by partial automation. This is captured in a novel ontology—a system of things that exist and relations between them—of existing techniques, identifying relevant techniques and showing how they relate (Figure 2). This ontology serves primarily to situate the partial automation approach introduced in this paper, while also providing a novel account of game accessibility techniques that will be of use to game designers in general. A new ontology was required as previous treatments of accessibility techniques for games have focused on a single approach (or sometimes two approaches [39]), and therefore have not allowed a clear exploration of how the techniques build on and complement each other. And of course no treatment to-date includes partial automation, as it is a new technique being introduced in this paper.

3.1 Universal Design

Games require that players be able to control all of the game's inputs. Sometimes these requirements restrict a game to a specific user group; for example, *Liberi* [50, 51] was designed for children with cerebral palsy at GMFCS level III (able to pedal a bicycle) [76] and MACS level II [24] (able to move a joystick and press a button) [57]. This choice shows how *Liberi* was influenced by *universal design*, which advocates that a product be accessible to everyone without adaptation [86]. Games designed according to universal design principles provide a "one size fits all" interface, but because no one size can truly fit everyone [97–99], people outside the target group are excluded [19]. For example, children at level IV of the GMFCS cannot play *Liberi* on their own. Designers can further restrict the abilities necessary to play, broadening the game's accessibility, but the resulting game may be seen as too simple for players who can do more.

There are two approaches to the universal design of games. Games can be designed to be broadly accessible, requiring only abilities that are widely held, such as the ability to press a button. Otherwise, designers can focus on a specific player population, such as people who use manual wheelchairs, and design for their abilities. As we will now discuss, both approaches make trade-offs to achieve universal accessibility.

3.1.1 Broad Accessibility. Games played using a single button or switch serve as exemplars of how broad accessibility can be achieved through universal design [101]. These one-switch games reduce interaction to the barest minimum of clicking a single button. Although one-switch games are nearly universally accessible, the design of these games is constrained by the simplicity of their common interface. For example, *Zac - O Esquilo* [67] is a one-switch version of the arcade game *Frogger* [58]. When the player presses the button, an algorithm moves the avatar in its chosen direction. Although this type of transformation through automation can make a game more accessible, a player who is capable of controlling a joystick might prefer the original version where it is possible to control the character's direction of movement. Thus universal accessibility comes at a cost to players with richer physical abilities.

Another class of broadly accessible games are games that players control with bodily movement. These ask players to run, walk, or push their wheelchairs around a physical space and use this movement to control the game. These games advantage players with superior mobility but remain accessible to anyone who can move around. For example, in *iGYM*, players move around the field of play to bounce a disc of light, projected onto the floor from above, into their opponent's net [43]. Play is simple, like *Air Hockey*, and that simplicity enables players who use walkers, wheelchairs, or no assistive device at all to play together. The same can be said of *Powered to Play*, a GPS-enabled, mixed-reality, capture the flag game designed for players who use powered mobility devices [23]. These games are accessible to players with vastly different abilities because only the ability to move around is required. However, players with limited mobility may need assistance to compete with more mobile opponents.

3.1.2 Focused Accessibility. Designers may choose to improve the accessibility of their game by narrowing its target population to players with specific abilities, such as the ability to pedal a bicycle or use a wheelchair. For example, the *Liberi* exergames were designed for children with cerebral palsy *who can pedal a stationary bicycle and use a gamepad controller* [50, 51]. This is different from designing for players with specific *conditions* that may cause disability, such as cerebral palsy or fetal alcohol spectrum disorder, whose abilities are unknown and in need of discovery [83]. For this approach to work, games need to be designed with consideration for what players are able to do, not what they are unable to do. Although these games are designed to overcome accessibility barriers encountered by disabled players, they extend access to a more focused sub-population defined in terms of their abilities. This is why audio games typically target players with vision impairments but are actually designed for players who can hear [93]. In this way, focused accessibility enables designers to make games accessible to a specific group of players with disabilities by designing for their abilities.

Many games have been designed specifically for players who use wheelchairs. Typically, these games use specialized hardware to turn the player's wheelchair into a game controller. For example, GAME$^{\text{Wheels}}$ uses wheelchair propulsion to control computer games [30, 94]. Players secure their wheelchair to a platform with rollers that control joystick interaction with the game. Manual wheelchair gaming interfaces and games have also been created using the Kinect [36–38, 52] and wheelchair mounted accelerometers [18]. These games are of course limited to players who can control a manual or power wheelchair.

Other focused games have been designed for players engaging in common rehabilitation exercises. For example, *Skyfarer* [40–42] is a mixed reality game that incorporates exercises from the STOMPS shoulder exercise protocol [71] into its control scheme. The player performs rowing exercises to navigate a sea-faring vessel, and collects water in a bucket by performing an external rotation exercise. Other games for rehabilitation require players to perform upper body exercises for wheelchair users [65], static balancing [11], seated balancing [12], calf raises [82], and arm ergometry [44]. These games are designed for persons requiring specific rehabilitation exercises, and so are inherently limited to those who can perform those exercises.

In summary, universal design is successful in creating inclusive games that a wide set of people can play. However, broadly accessible games may still advantage some players over others and games with focused accessibility exclude players whose abilities are different than the target group. As we shall see in the next section, adaptations for players with motor impairments can help to overcome both of these limitations.

3.2 Game Adaptation

As described above, even games designed to be broadly accessible can exclude players whose motor abilities do not match the requirements of the game. When this happens, games need to be adapted so that disabling aspects of play are removed. Two popular game adaptations are: *interface adaptation* and *player balancing*. Interface adaptation provides an alternative hardware interface designed around the abilities of excluded players. Player balancing techniques compensate for deficits in players' performance, making games easier to play and enabling weaker players to compete with stronger opponents. Both approaches have been, and continue to be, instrumental to improving games accessibility. As suggested by Figure 2, interface adaptation and player balancing can be used together to further extend a game's accessibility. In this section, we describe how these approaches work, how they can be combined, and how partial automation complements them.

3.2.1 Interface Adaptation. Players who are disabled by a game's controls are unable to play without an accessible alternative. When many players are unable to use the same part of a game's controller, designers can create an *alternative interface* to overcome the barriers that these players encounter. When making rehabilitation games more accessible, designers need to enable players to perform the same exercises using the new interface. For example, Mat Rosly et al. designed a paddle-like sleeve for the PlayStation Move that makes it easier for players with tetraplegia to press buttons in a kayaking game [66]. Thirumalai et al. adapted the *Wii Fit* [21] Balance Board for players who use mobility devices such as walkers and wheelchairs [89]. The adapted Balance Board eases play for persons with mobility disabilities through a ramp for wheelchair access, a large platform, handrails to aid balance, a dedicated "jump" button, and adjustable center of balance sensors [63, 64]. This device made *Wii Fit* accessible to players with a broader range of motor abilities, from those who could stand and balance using a handrail to those who could lean in their wheelchairs. This extends the group that can play, but the adapted Balance Board may still be inaccessible to players whose abilities are different from the target population. For example, a player with complete tetraplegia may have insufficient center of balance control to overcome balancing challenges. Although creating alternative interfaces can greatly improve game accessibility for players with homogeneous abilities, designers may need to make multiple interfaces, incurring additional development overhead, to provide broader accessibility. This limits the efficacy of this approach for adapting existing games for populations with large differences in individual ability.

When players are disabled by different aspects of the game's interface, it may be possible for individuals to play using a *personalized interface* made up of multiple accessible controllers. Heuristics for accessible game design, such as the Game Accessibility Guidelines [2] and Accessible Player Experiences [1], promote features allowing players to remap inaccessible game inputs to accessible parts of a game's controller. This can greatly increase games accessibility for players who can use the default controller with some difficulty, but is incapable of making games accessible to players who cannot use the controller at all. Solutions such as the Xbox Adaptive Controller, the interface device of Iacopetti et al. [54], and the AsTeRICS framework [75] overcome this limitation by enabling players to create their own bespoke interfaces. They allow players to control each of a game's inputs using a separate, accessible device, enabling players with different abilities to play the same games by virtue of personalization. However, this approach requires that players control all aspects of play, which may not be possible if accessible alternatives are unavailable or are themselves too difficult to use.

3.2.2 Player Balancing. Another major form of game adaptation is player balancing. Player balancing mechanics help weaker players to compete with stronger players [9]. Unlike game balancing, which presents challenges of the same difficulty to all players, player balancing personalizes a game's difficulty to the abilities of individuals. For example, first-person shooter games have historically provided *aim assistance* for players who aim using analog sticks, since analog sticks are less precise than the mice used by other competitors [96]. As with interface adaptation, designers using player balancing to make serious games more accessible need to ensure that aspects of play that are essential to a game's serious purpose (e.g. the exercise in an exergame) are still challenging enough to provide benefit.

Balancing for player skill has been shown to enable more engaging social play [53, 70], increase relatedness among competitors [39, 56], and reduce differences in performance [9, 53, 56]. In a study by Hwang et al., participants with different levels of fine-motor and gross-motor function competed in a cycling-based racing game and an analog-stick-based shooting game, either with or without balancing for differences in players' motor abilities [53]. It was found that competitions in which balancing was used had closer outcomes and were perceived as more fair by players. These results indicate that player balancing techniques can be used to help players with motor impairments overcome challenges that would be too difficult otherwise. However, player balancing is inherently limited to situations where players have at least some ability to use the provided interface. For example, Hwang's balancing techniques do not work for players who cannot cycle or use an analog stick at all.

3.2.3 Combining Approaches. Interface adaptation and player balancing both extend games' accessibility to players who are excluded due to motor impairment. When combined, each technique can help to overcome the limitations of the other. This was the approach taken by Gerling et al. when designing *Wheelchair Revolution* [39], a clone of *Dance Dance Revolution* [10] adapted for players who use wheelchairs. In *Dance Dance Revolution*, players stomp in time with music on an array of buttons, called a dance mat. To enable play using a wheelchair, a Kinect-based action recognition system, called KINECT$^{\text{Wheels}}$ [37], was used to transform wheelchair movements into game inputs. This alternative interface enabled players who used wheelchairs to play the game with players who used the dance mat, but it was unknown whether competition between players with such radically different motor abilities would be fair. To account for their differences, Gerling et al. used player balancing algorithms that decreased the number of movements required of weaker players, made timing movements easier, and scaled scores by a personalized score multiplier. Although dance mat players generally performed better than their wheelchair player opponents, player balancing had a positive effect both on competitors' feelings about competing against opponents with different abilities and on wheelchair players' experiences of enjoyment, autonomy, competence, and relatedness during play.

These results indicate that games that employ interface adaptation and player balancing can be accessible to players with different motor abilities. When players are able to play the game in their own way, differences in physical ability have less effect on players' performance and experience. However, the efficacy of these techniques has limits. Players for whom no adapted interface is accessible are unable to play and therefore cannot benefit from player balancing. For some players, no interface adaptation or player balancing technique can make all aspects of a game accessible. This is the problem addressed by the present work: how can we make games accessible to players who are unable to control some inputs? In search of a solution, we look further afield at an approach to the design of accessible interactive systems, called *shared control*, as exemplified by our partial automation technique (Section 2). In the next section, we explain what shared control is, and review its emergent use in accessibility.

3.3 Shared Control

In this approach, multiple users share control of a system designed for a single user [60]. Often, the system's primary user shares control with a singular partner, which might be naturally or artificially intelligent. For example, *smart power wheelchairs* [20, 27, 28, 59, 61, 62, 87] and *mobility assistance robots* [35] have been enhanced with shared control AI that help their user to avoid obstacles, steer smoothly, or recover from mishaps. The shared control strategies employed by these algorithms fall into two categories according to how control responsibilities are divided between the user and their partner, called *sharing* and *trading* [49, 55, 85]. *Sharing* systems assign control of each system input to either the user or their partner while *trading* systems allow the user and partner to both control an input, for example with the partner supervising and correcting the user's actions. In this section, we describe how these two approaches have been used to make interactive systems more accessible.

Of the two, the *trading* control approach is more commonly used for improving the accessibility of interactive systems. For example, Soh & Demiris trained smart power wheelchairs to trade control with users experiencing difficulty [87]. When this happens, the AI temporarily takes control to help the user out. This approach was inspired by the hand-over-hand method—moving the user's hand to demonstrate how a task is to be executed—used by occupational therapists. A similar approach has been used to make recreation activities accessible to people with motor impairments [3, 8]. Alsaleem et al. demonstrated that *trading* control made both skiing and sailing accessible to persons with tetraplegia. Users were asked to control a skiing or sailing apparatus with either a joystick or sip-n-puff controller while their control partners supervised and provided assistance [4, 5]. This enabled users to participate in these activities safely and with as much independence as possible.

Control *trading* is also used in Xbox consoles' Copilot feature that allows players to share or trade control with a human partner.

In games, *trading* control can be used for player balancing. For example, as mentioned before, Hwang et al. used aim assistance to balance for differences in players' fine-motor abilities. Unlike other forms of aim assistance, which do not affect the player's control directly [96], Hwang's algorithm briefly trades control of the aiming input when a shot is fired, refining the player's aim to point directly at their opponent [53]. Trading-based assistance was also implemented by Cechanowicz et al. in a racing game [17]. So long as the player used the game's steering input, a player balancing algorithm gently adjusted their steering direction to align with the direction of the road. *Mario Kart 8 Deluxe* [22] also provides steering assistance that turns the player's avatar when they are in danger of driving off the race track. In this way, *trading* control inherits the limitations of player balancing; it can assist players who have difficulty controlling an input but offers no benefit to players who cannot control that input at all.

Sharing control presents a promising new approach to making interactive systems more accessible. This approach was illustrated in the *Alienated* one-switch game [78], an accessible remake of the classical *Space Invaders* game. In *Alienated*, the player controls movement of the base station at the bottom of the screen, while AI controls shooting of the aliens.

Our own technique, partial automation (as described in Section 2), provides control *sharing* with the novel enhancement of being personalizable. A partially-automated version of *Space Invaders* would allow players who can manipulate a joystick to control the base's movement, and players who can press a button to control firing. This would allow players to control all of the inputs they can, and to receive AI support for those inputs they cannot control. This personalizes players' control and enables them to take full advantage of their abilities.

We hypothesized that *sharing* control through partial automation could broaden a game's accessibility to players with vastly different physical abilities and personalize control of the game to the abilities of individual players. This is the first paper to investigate whether sharing control with an AI partner can improve the accessibility of digital games. To find out, we implemented partial automation in two exergames and conducted an exploratory study. We asked six participants with vastly different motor abilities due to spinal cord injury to play both games with the help of an AI agent. We now introduce these games, and in the following section, we present the study.

4 EXAMPLES: *DINO DASH* AND *DOZO QUEST*

We have demonstrated partial automation in *Dino Dash* and *Dozo Quest*, two games from the *Liberi* suite [50, 51], now targeted to support rehabilitation of spinal cord injury. These are fast-paced action games presented in an amusing cartoon style. In *Dino Dash*, players compete to be the first to collect eggs and bring them at their nest. In *Dozo Quest*, players navigate a desert dungeon, defeating enemies, until they arrive at a final "boss" enemy. Players control their avatar's movement speed by pedalling a bicycle, select the avatar's direction using a joystick, and activate a "dash" action using a button. The games are modified to use the MOTOmed viva2 pedalling device, widely used in spinal cord injury rehabilitation to improve muscular strength and range of motion [73]. The viva2 supports both active pedalling and passive pedalling, where the device's motor provides the pedalling action.

In both games, players provide the three types of input suggested in Figure 1: *Movement* determines the avatar's movement speed and is controlled by the player's active or passive pedaling; *Direction* determines the direction of movement and is controlled with a joystick such as a gamepad's left analog stick, and *Action* is a context-sensitive action in the game (e.g., jump or attack), controlled by pressing a button such as a gamepad's "A" button.

Fig. 3. *Dino Dash*. Players gather eggs and bring them back to their nest. The player is controlling a red dinosaur that is shouting, stunning the yellow dinosaur in front of it.

Dino Dash is an action game where players control a colourful dinosaur that collects eggs and brings them back to its nest. Red, yellow, green, and blue dinos chase each other around the game's arena, stunning the others with projectiles and stealing their eggs (Figure 3). Players pedal the bike to make their dino move and steer using the left analog stick to avoid patches of mud or line up shots. After the player has pedalled quickly for some time, they can press any of the gamepad's face buttons to make the dino perform a "shout" that briefly stuns opponents in front of it, causing them to drop their eggs. The first player to collect ten eggs wins.

In *Dozo Quest*, the player explores a dungeon, clashing with enemies along the way, to find and defeat a final boss. The player's avatar is a spiky red ball, called a dozo, that can roll along the ground and do a dash attack to hurt enemies. The faster the player pedals the bike, the faster the dozo moves. Its movement direction is controlled with an analog stick. To defeat enemies that float above the ground, the player must pedal quickly, tilt the analog stick upwards to jump, and press any gamepad face button to dash (Figure 4). Should the player's dozo run out of health points, it is resurrected at an earlier checkpoint.

4.1 Universal Design in *Dino Dash* & *Dozo Quest*

The *Liberi* exergames were designed for children with cerebral palsy and are therefore able to accommodate players with significant motor impairment. In accordance with universal design principles, controlling the games involves abilities that are widely held by target players: the ability to pedal a specially designed bicycle, the ability to use an analog stick, and the ability to press a button. These games were chosen for our study because this range of motor abilities is held by some but not all persons with spinal cord injury. Some players would be unable to play without adapting the games, allowing us to determine whether partial automation made them accessible. Design choices, such as having each of the gamepad's face buttons trigger actions, may make *Liberi* more accessible than other exergames for players with spinal cord injury, but we knew that the involvement of pedalling would make it inaccessible to many.

To overcome the accessibility limitations of *Dino Dash* and *Dozo Quest* for players with spinal cord injury, we used interface adaptation and partial automation to allow players greater flexibility

Fig. 4. *Dozo Quest*. The player navigates a maze to defeat the final boss. The player is controlling the red ball to hit a "mufu" enemy with its spin dash attack.

in how they play, a strategy suggested by Figure 2. Specifically, players who could not use the gamepad were offered a joystick to replace the analog stick and a mouth button to replace the gamepad buttons. If neither joystick was accessible, then direction input was automated using an AI agent.

Partial automation was used when necessary for pedalling input. In spinal cord injury rehabilitation, patients use a passive cycling device such as the *MOTOmed viva2* to improve strength and range of motion in their leg muscles [73]. This viva2 device was used for pedalling input. For players who are unable to pedal, the viva2's motor pedals for them, and control of the pedalling input is automated.

Our use of a universally designed game, now enhanced with interface personalization and partial automation, shows how these three separate techniques can be combined to make the same game accessible to players with motor impairments ranging from minor deficits in manual dexterity to complete paralysis below the neck. In the rest of this section, we describe how participants personalized their interfaces and how game playing AI was used to automate inaccessible inputs.

4.2 Personalizing *Dino Dash* and *Dozo Quest*

Building on universal design, the games' accessibility was enhanced using interface personalization and partial automation, as suggested by Figure 2. With partial automation, *Dino Dash* and *Dozo Quest* players control whatever inputs they can, using an accessible, personalized hardware interface. Some people with spinal cord injury can pedal a bicycle and use a gamepad controller, and so can provide their own Movement, Direction and Action inputs using these devices. Others have paralysis below the neck and can perform their own Action inputs with a bite switch, while AI automates their Movement and Direction inputs. Players use different devices to play the games, depending on their physical abilities. Our strategy is that if an input can be made accessible by substituting a different input device, we do so – for example, substituting a bite switch for a button on a controller. If no device makes an input accessible, we automate that input. Partial automation is therefore a last resort, to be used when traditional accessibility techniques are insufficient. We now describe the input devices selected for people with spinal cord injury.

Fig. 5. Participants playing *Dino Dash* and *Dozo Quest* with different devices. Left: A man with complete paraplegia playing *Dozo Quest* using the gamepad to provide Direction and Action inputs. The viva2 is pedalling, and so AI provides Movement input. Center: A woman with incomplete tetraplegia playing *Dino Dash* using a joystick and bite switch to provide Direction and Action inputs. The viva2 is pedalling for her, and so AI provides Movement input. Right: A man using a MOTOmed viva2 (left of image) for rehabilitation of spinal cord injury. The viva2 is a pedalling device where the users' feet are secured to the device while they sit in their own wheelchairs. The device's motor moves the pedals for users who are unable to pedal for themselves.

4.2.1 Movement Input. Movement is controlled using the *MOTOmed viva2* (Figure 5), a cycling device used in spinal cord injury rehabilitation. People who can pedal use the viva2 like a regular stationary bicycle, providing the Movement input to the game; the faster the player pedals, the faster the avatar moves. If the user cannot pedal, the device pedals for them using a built-in motor, providing therapeutic activation of the leg muscles [73]. In this case, Movement is automated, controlling when and how fast the player's avatar moves.

4.2.2 Direction Input. The player uses either the analog stick on a Logitech F710 gamepad (Figure 5–left) or a HORI Fighting Stick Mini 4 joystick (Figure 5–center), whichever they find easier, to control their avatar's movement direction. If they cannot control either device, choice of direction is automated by the AI (Figure 5–right).

4.2.3 Action Input. All of the gamepad's face buttons can trigger the Action input. Players who are unable to use the gamepad instead use a Glassouse bite switch to provide Action input (Figure 5–center & right). This is a small button that users hold in their mouth and bite to activate.

We hypothesized that partial automation, in conjunction with this flexible collection of input devices, would make *Dino Dash* and *Dozo Quest* accessible to players with vastly different abilities due to spinal cord injury. For example, Figure 5–center shows a player using a personalized configuration of input devices and automation. She uses the joystick to control the Direction input, and uses the bite switch to provide Action inputs. A second player, shown in Figure 5–left, has complete paraplegia and cannot pedal the viva2 to control the Movement input. This player uses the gamepad to control Direction and Action, with the Movement input automated. A third player (Figure 5–right) has complete tetraplegia, and plays using a bite switch to control the Action input, while the Movement and Direction inputs are controlled by the AI. The input devices used to play

Table 2. The list of *Dino Dash* and *Dozo Quest* inputs that each hardware device can control.

Input	Device	Use in *Dino Dash* and *Dozo Quest*	Automation
Movement	MOTOmed viva2	Determines avatar's speed	Controls when and how fast the avatar moves
Direction	Gamepad or joystick	Determines avatar's movement direction	Controls what direction the avatar moves in
Action	Gamepad or bite switch	Triggers Dino's shout and Dozo's dash	Controls the avatar's actions

Dino Dash and *Dozo Quest*, the inputs they provide, and how they are automated, are summarized in Table 2.

4.3 Automating *Dino Dash* and *Dozo Quest*

Building on universal design and interface personalization, the final step in making *Dino Dash* and *Dozo Quest* more accessible is partial automation, as illustrated in Figure 2. To achieve this, we created custom AI agents to automate play of each game. The agents operate by injecting inputs into the game mimicking inputs that a player would provide. As mentioned in Section 3, designers using partial automation should take care not to remove the exercise component of rehabilitation games. Since pedalling the viva2 may be performed either by the user or by its built-in motor, automating the Movement input in *Dino Dash* and *Dozo Quest* does not diminish the utility of these games in spinal cord injury rehabilitation. Both agents were implemented at the level of the games' source code and have complete knowledge of the games' states. To be successful, these agents need to follow strategies that play the game well and that perform actions that the player would expect.

The *Dino Dash* agent uses classic game AI steering behaviour [68] to navigate the play area using the Direction input. The agent transitions between behaviour states depending on its surroundings. For example, when a nearby dino is carrying an egg, and there are no free eggs nearby, the agent will transition to *chase mode* and prioritize chasing down the dino to steal its egg. Attractive and repulsive forces exerted by game objects determine how fast the avatar moves using the Movement input. For example, a free egg exerts a large attractive force that causes the avatar to move at full speed towards it. If the agent is not carrying an egg and encounters another dino within a short range ahead, it uses its shout to stun the opponent by triggering the Action input. These behaviours enable the agent to independently control any subset of the game's three inputs, no matter which inputs are controlled by the player.

The *Dozo Quest* agent moves from room to room in search of enemies, targeting whichever enemy is closest. When a new enemy is targeted or the dozo is knocked off course, the agent uses the A* pathfinding algorithm [68] to plan a path from its current location to its target's location. The agent uses the Direction input to direct its movement along the path and the Movement input to roll along at top speed. Once in range of one or more enemies, the agent aims directly at the closest one, gets closer, and dashes at it using the Action input. Sharing control of *Dozo Quest* involves both the player and the agent coordinating their control of the Movement, Direction, and Action inputs to perform complex actions like the dash attack. No matter which inputs are controlled by the player or the agent, both need to coordinate their actions to play effectively.

The algorithms used by our *Dino Dash* and *Dozo Quest* agents were chosen because they are easy to understand and implement. Agents deployed in other games may require significantly different architectures. For simple games, agents' plans could be expressed using planning models [68], such as hierarchical finite state machines (HFSM), behaviour trees, or goal-oriented action planning (GOAP). In more complicated games, agents' policies could be learned [100] as a belief-desire-intention model [26], a deterministic policy through deep Q-learning [69], or a stochastic policy through proximal policy optimization [84]. As a model-agnostic approach, partial automation affords designers limitless freedom to choose AI algorithms that cooperate well with players.

These examples of *Dino Dash* and *Dozo Quest* show that it is possible to develop games that use partial automation with the goal of increasing the games' accessibility. With these games, we have demonstrated that it is possible to start with a base of universal design, extend accessibility using interface personalization, and then, finally, use partial automation only when these techniques are insufficient. This allows a game to have full features available to persons who can use a game

Table 3. Participants' demographic information. NLI (Neurological Level of Injury) specifies the part of the spine that was injured. The Movement, Direction, and Action columns indicate the devices participants used to control each input ("V"=viva2, "G"=gamepad, "J"=joystick, "B"=bite switch; no device indicator means input was automated).

Code	Age	Sex	AIS Grade	NLI	Movement	Direction	Action
P1	31	M	Incomplete Paraplegia (C)	T11	V	G	G
P2	33	M	Incomplete Tetraplegia (B)	C4	V	G	G
P3	31	M	Complete Paraplegia (A)	T5		G	G
P4	23	M	Complete Paraplegia (A)	T4		G	G
P5	33	F	Incomplete Tetraplegia (B)	C5		J	B
P6	28	M	Complete Tetraplegia (A)	C4			B

controller and a pedalling device, while still allowing play be people who cannot use a joystick, or who rely on the viva2's passive pedalling.

In the next section, we explore the success of partial automation in making the games accessible to persons with vastly different physical abilities due to spinal cord injury, and explore their experience with play of these games.

5 STUDY DESIGN

We performed an exploratory study to find out whether this combination of universal design, interface personalization, and partial automation made *Dino Dash* and *Dozo Quest* accessible to six participants with vastly different physical abilities due to spinal cord injury. This study was approved by the research ethics boards of all institutions involved. All participants were outpatients at a local rehabilitation hospital and had prior experience using the *viva2* motorized cycling device. The viva2 moves patients' legs during rehabilitation if the patients cannot pedal [73]. Participants played both *Dino Dash* and *Dozo Quest* with personalized levels of partial automation. The study's key data sources were responses to a semi-structured interview conducted at the end of each session and game log files capturing participants' ability to play. Transcripts of the interviews were analyzed using reflexive thematic analysis [14–16] to identify themes between participants' reported experiences. The study addressed two research questions regarding the efficacy of using partial automation to make exergames accessible to people with spinal cord injury. They are:

- **RQ1:** *Does partial automation make* Dino Dash *and* Dozo Quest *more accessible?* — Does partial automation make these games accessible to players with a wide range of motor impairments due to spinal cord injury, while complementing other accessibility techniques?
- **RQ2:** *What is it like to play with automation?* — What are players' experiences of playing *Dino Dash* and *Dozo Quest* with partial automation?

5.1 Participants

Participants were required to have spinal cord injury, be an in/outpatient at the hospital, be 18 to 50 years of age, have at least fifty hours of lifetime videogaming experience, and be able to engage in an interview. They were recruited by a spinal cord injury physiatrist at a local hospital and via a poster that was circulated to members of a community organization. Six participants met with us individually in the hospital's outpatient gym for a single 90 minute session.

Table 3 shows the participants' demographic information, including the game inputs that the AI controlled during play. In spinal cord injury rehabilitation, patients' motor and sensory abilities are classified using the ASIA impairment scale (AIS) [80]. A patient's AIS letter grade indicates their level of motor function below where they were injured (neurological level of injury – NLI), ranging from A to E. An E indicates normal motor function, D and C mean some impairment, and patients with B and A have complete impairment. Participants' information indicates that they had vastly different physical abilities, ranging from AIS grade C paraplegia where the participant could pedal a bicycle and use a standard game controller, through to AIS grade A tetraplegia where the participant could interact with the games using only a bite switch.

5.2 Method

Participants were invited to the hospital's outpatient gym to play *Dino Dash* and *Dozo Quest* with personalized partial automation. Upon arrival, participants were guided through the study's informed consent procedure and asked to complete a demographic questionnaire. Participants who were unable to sign the consent form or fill out questionnaires were assisted by their care worker or the researcher conducting the session.

Participants' physical abilities were assessed by the physiatrist. They were first asked if they could use each of the games' default devices. If not, participants were provided with a personalized interface, and inputs that participants could not control with any device were automated. Each participant was asked whether they could pedal the viva2 and use the gamepad. If they could not pedal the viva2, the device's motor pedalled for them and the Movement input was automated. If participants did not believe they could use the gamepad, they were asked if they could use the joystick or bite switch. Participants played with a selection of accessible devices matched to their abilities, listed in Table 3. Before playing each exergame, the participant's physical condition was assessed by the physiatrist to confirm their fitness to continue.

Participants then played each exergame for approximately five minutes. We explained to participants the games' mechanics and goals, as well as how the inputs under their control affect their avatar's activities. They first played a warm-up round of each game to verify that they understood how to play. We did not tell them that control over some of the avatar's activities would be automated or explain how the games were played using the inputs that they did not control. This was done to determine whether participants could determine how to play the games using only the inputs that were accessible to them. Participants played two rounds of *Dino Dash* and one round of *Dozo Quest*, totalling roughly five minutes for each game. Following play of all of the rehabilitation games, participants engaged in a semi-structured interview about their experiences.

5.3 Data Collection

Three forms of data were collected during sessions: (1) a demographic questionnaire, (2) gameplay logs and video of gameplay, and (3) a semi-structured interview. The demographic questionnaire recorded participants' age, sex, AIS classification, neurological level of injury (NLI), and their gaming experience both before and after their injury. During play of the *Liberi* exergames, successful performance of key game activities was recorded. In *Dino Dash*, these were moving, steering, picking up an egg, scoring a point, and hitting another Dino with a shout. In *Dozo Quest*, recorded events were moving, steering, and hitting an enemy with a spin dash. The presence of these events in the gameplay logs shows the degree to which participants were capable of engaging in all aspects of play.

Following play of both exergames, participants were interviewed for approximately thirty minutes about their overall experience and experience playing each of the exergames. We asked them whether they liked each game and whether they experienced fun, difficulty, or frustration while playing. We also asked about significant moments during play, whether they liked the pace of the games, and whether they felt like they were in control while playing. These interviews were video-recorded to allow later analysis.

Table 4. Players abilities to carry out gameplay actions in the rehabilitation games. A ✓indicates that the participant performed the action at least once during gameplay. A ˜ indicates that an error prevented gameplay data collection.

	P1	P2	P3	P4	P5	P6
Dino Dash						
Moved	✓	✓	✓	✓	✓	✓
Steered	✓	✓	✓	✓	✓	✓
Hit an opponent	✓	✓	✓	✓	✓	✓
Picked up an egg	✓	✓	✓	✓	✓	✓
Scored a point	✓	✓	✓	✓	✓	✓
Dozo Quest						
Moved	✓	✓	˜	✓	✓	✓
Steered	✓	✓	˜	✓	✓	✓
Hit an enemy	✓	✓	˜	✓	✓	✓

In the next two sections, we present the results of our analyses. Gameplay data were analyzed to determine if partial automation enabled participants to play the games (RQ1: Does partial automation make *Dino Dash* and *Dozo Quest* more accessible?). Qualitative data were analyzed to provide insight into participants' experiences of playing *Dino Dash* and *Dozo Quest* with partial automation (RQ2: What is it like to play with automation?).

6 RESULTS: ABILITY TO PLAY

As shown in Table 3, the use of interface personalization and partial automation allowed participants who would have been disabled by the games' default interface to play in a different way. P5 and P6 were unable to use a game controller, but benefited from alternative devices: P5 was able to control the Direction input with the joystick, and both were able to control the Action input with the bite switch. Partial automation extended the improved accessibility provided by interface personalization even further. Four of six participants were unable to pedal the viva2 but were able to play using passive pedalling and the assistance of partial automation to determine when and how fast their avatar should move. This combination of approaches helped participants to overcome otherwise disabling accessibility barriers.

We manually reviewed recordings of participants' gameplay to determine which gameplay actions they were capable of performing, either on their own or with the assistance of AI. These data, captured in Table 4, show that with the assistance of automation, all participants were able to use all features of *Dino Dash* and *Dozo Quest*. This included core functions such as moving the avatar, and game mechanics such as picking up objects and attacking enemies.

From this, we conclude that the use of partial automation to personalize *Dino Dash* and *Dozo Quest* was successful in extending access to full-featured games. We found that participants with vastly different physical abilities, ranging from people who could pedal a bicycle and use a gamepad to people who were capable of interaction only through a single bite switch, were able to play both games. This establishes that for these two games, partial automation met its primary objective of making the games accessible to people with vastly different physical abilities, ranging from minor deficits in motor control, to complete paralysis.

This success in increasing accessibility, however, does not reveal whether players enjoyed partial automation, or were even aware of its effects. The next section reports on players' experiences with partial automation.

7 RESULTS: PLAYER EXPERIENCE

One member of the research team watched and sequentially transcribed video of participants' sessions and semi-structured interviews. Transcripts were analyzed using reflexive thematic analysis from a realist perspective informed by the gameplay logs. Participants' statements about gameplay events, like winning the games or strange AI behaviour, were compared with gameplay recordings. This was done to discover how partial automation influenced participants' experiences. Transcripts were coded inductively with consideration for their explicit semantic content. In particular, we were interested in participants' reported experiences of using partial automation. One researcher coded the data and proposed an initial set of themes which were then discussed in depth with two other researchers while making reference to the original transcripts. Through this process, we identified two major themes, which over several meetings were refined and reorganized into major themes with minor sub-themes.

Participants' experiences of playing exergames with partial automation were strongly positive. Participants found that the games were far more accessible to them than other games they had tried to play since their injuries. Participants were sensitive to the accessibility needs of others with different abilities. They believed that partial automation would greatly increase the accessibility of exergames for others with motor impairments. As stated by P5: " [Partial automation] *opens up an avenue for people with different types of disabilities and different types of abilities to be able to play.*"

In this section, we report two major themes: *Adaptation Both Includes And Excludes* and *Automation Confusion.*

7.1 Major Theme: *Adaptation Both Includes And Excludes*

Participants believed that partial automation would enable players with different abilities to play the same games, but recognized that players' experiences may be different. The games' hardware interfaces and mechanics allowed participants to take advantage of their unique abilities to make play uniquely meaningful to them. However, some parts of these games indicated to participants that play may be better for others with abilities they lacked. In this section we describe two minor themes related to participants' experiences of inclusion and exclusion.

7.1.1 Minor Theme: *Adaptation Makes Players Feel Able.* Playing *Dino Dash* and *Dozo Quest* with an adapted hardware interface enabled participants to play in their own ways. They liked using devices that were similar to devices they use in daily life and wanted to personalize their interfaces further using their own devices. One unintended benefit of partial automation is that it allows players to delegate control of unwanted inputs and focus on inputs that are most important to their rehabilitation (i.e., controlling Movement by pedalling the viva2). This theme illustrates how revisiting familiar game mechanics and using familiar devices made participants feel accomplished when they were able to employ their existing skills to play.

Participants wanted to play using devices that they use in daily life and found that using familiar devices can make players feel competent. P5 has incomplete tetraplegia and drives her power wheelchair using a joystick. She showed us the trick she uses to grip long objects and said that the same trick would enable her to use the joystick to play. We placed it on the table to her right (Figure 5–center) and she said: "*I should have no problem with this.*" P6 also uses a power wheelchair and brought his own devices to the session. While playing both games with the bite switch, he tilted his head from side to side, as if to direct his avatar in that direction. During his interview, he explained how he would have liked to use his power wheelchair's head controls to play: "*I think that would be an opportunity to use an already existing control, that the person already knows, to be able to control what they want to do on the games.*" A game that supports power wheelchair controls may have enabled P6 to leverage his unique abilities.

Beyond this desire to use familiar devices, participants found that feeling rewarded for their expertise made play meaningful to them. P4 identified *Dozo Quest* as a *Metroidvania*-style game, which made it immediately familiar to him. He believed that his expertise in this style of game enabled him to quickly learn to play. "*I was given the tools right off the bat, and since the controls were simplistic enough I was able to pick that up quick.*" (P4) Although he described *Dozo Quest* as giving him the tools, it may be more appropriate to say that P4 brought his own tools, which *Dozo Quest* enabled him to use. P2 liked that the dozo jumped higher when he pedalled faster. He said that this provided him with feedback that indicated how well he was pedalling and rewarded him for doing more vigorous exercise. "*Getting him to jump a certain way or using the button for that burst only worked if you had that speed built up. So, the more speed you had the more lift you can get...*" (P2) The mechanical similarities that *Dozo Quest* shared with games P4 had played before and its jump mechanic, which rewarded P2 for pedalling quickly, gave them the impression of being rewarded for doing things they are good at doing.

Personalizing control of the games afforded participants greater freedom to choose how they play and automation may have enabled participants to focus on the most important aspects of play. When asked how *Dino Dash* could be improved, P1 said that he might have preferred to play without the gamepad, so he could focus more on pedalling. This answer was surprising; other participants wanted more control over the games, not less. He explained that playing *Dino Dash* distracted him from cycling. "*You'd wanna be more focused on your workout, wouldn't it? ... Just 'cause the game, it's distracting you...*" (P1) His priority was getting a good workout and he wanted to personalize his control of *Dino Dash* to provide the highest quality exercise.

7.1.2 Minor Theme: *Adaptation Makes Players Feel Disabled.* In contrast to the positive experiences described above, participants described past negative experiences with inaccessible exergames, which raised concerns about whether the games they were testing would be accessible. They wanted exergames to be accessible both to them and also to others with different abilities. They felt disabled by previous games they could not play, but also felt disabled by games that required them to play differently from other people. One participant explained that playing with partial automation gave him the impression that he had a diminished experience of play. This theme illustrates how adaptations for players with motor impairments can make them feel disabled, even when the adaptations allowed them to play the game.

Specifically, past negative experiences with inaccessible games coloured players' expectations entering this study. P5 explained that since her injury, exergames that use the Kinect have been inaccessible to her. "*It took me like an hour using the regular remote, and like I said, to make up this avatar. And then it was like* `` `please stand in front of the sensor'``. *So, it was like it wouldn't recognize the lower half of my body.*" (P5) Even though she could use the gamepad to customize her avatar, Kinect gaming was inaccessible to her because she lacked the ability to stand.

Even when they could play other games, participants sometimes believed that play was better for others with different abilities. P4 talked about *Beat Saber* [32], a virtual reality rhythm exergame that he plays at home. In *Beat Saber*, players swing motion controllers to slice colorful cubes to the beat of the music as they move side-to-side and duck to avoid oncoming obstacles. *Beat Saber* can provide vigorous exercise for standing players, but P4 uses a wheelchair. He described the way that he plays as inferior to how others play: "*Let's say that someone who can stand and move around to some degree, it would certainly suit them a lot better than it would me... When you're standing,* *again, you've gotta move your body, but you have to move your whole body rather than just, you know, moving your... just kinda tilting your head.*" Even though he can play *Beat Saber*, P4 believed that play would be better for those who can stand.

As a consequence of these prior negative experiences, adapted interfaces can make players feel disabled, even when they are able to play. P6 recognized that players who can pedal the viva2 were able to control aspects of play that he could not, which he found diminished his experience: "[Playing the games] *relied on what you were putting into, kind of like, the* [viva2] *as well. That's a component of it. So, not being able to change what the input into the* [viva2] *would be is just kind of the diminishing part of it.*" (P6) He said that using the viva2 as part of the games' hardware interface indicated to him that they were not designed for him. We asked P6 if he believed that he missed out in playing *Dino Dash* and *Dozo Quest*. Although he recognized that there were parts of the games that he could not control, P6 said that he preferred being able to play in a limited way over not being able to play at all.

7.2 Major Theme: *Automation Confusion*

We explained to participants how to play each game using the inputs under their control, but did not explicitly explain that an AI agent would be controlling aspects of the avatar's behaviour. This confused two participants who noticed that some of their avatars' activities were automated, making it more difficult for them to identify inputs under their control and learn how to play. In this section, we describe two minor themes related to the confusion participants experienced due to automation.

7.2.1 Minor Theme: *Understanding Source of Avatar's Behaviour.* Of the four participants who played with partial automation, only those who had difficulty coordinating their control with the AI noticed its effects. Participants who were aware of the automation sometimes found it difficult to recognize how their inputs changed their avatar's behaviour. This theme explores how participants made sense of partial automation and how it affected their experiences.

When the AI performs actions that players expect, players may not notice the automation. Only two participants recognized that their avatars' activities were not fully under their control. When asked if he believed he was in control while playing *Dino Dash*, P4 replied: "*Yes, fully in control!*" P4 played using the gamepad with the games' Movement input automated. P3 used the same hardware interface as P4 and when asked the same question he gave a similar answer. Neither participant indicated that they were aware they had less than full control of their avatar in both *Dino Dash* and *Dozo Quest*.

Players became aware of the automation, however, when the actions of the AI agent made the game more difficult to play. P5 noticed the effects of automation while playing *Dino Dash*. She played using the joystick and bite switch with Movement automated, which made her dino move forward constantly. She found this difficult to control, saying: "*It was always in motion and I'm only... You're only controlling like the direction that it goes in, and I was trying to control everything about it.*" P5 did not experience this confusion while playing *Dozo Quest*. She believed that she could control the dozo's speed even though this was under AI control. When asked if she had difficulty playing *Dozo Quest*, she said: "*No, I could control it all so it was great!*" P5 was only aware that the Movement input was automated when it made playing more difficult.

Since both the participants and their AI partners controlled the avatar, automation made it unclear to the player what they could control. P6 played using the bite switch, with both Movement and Direction automated. He controlled only one of three inputs in *Dino Dash*, and was unsure which aspects of the dino's activities could be attributed to him. During the interview, he was uncertain if he was able to affect the dino's direction. He said: "*It was just hard to tell, when I was trying to move* *the dinosaur in the right direction, about how to do that properly and stuff.*" P6 encountered similar confusion while playing *Dozo Quest*. He said that "[*Dozo Quest*] *was still another one that was, like, hard to figure out what was doing what, and how to kind of go about it.*" Although he was able to correctly identify the dozo's dash attack as an action under his control, he was unsure if there were more.

7.2.2 Minor Theme: *Learning to Cooperate with Partial Automation.* When participants recognized that there were aspects of the games that they did not control, it made play more difficult. Even when the AI's behaviour was predictable, participants had difficulty coordinating with it. One participant found it frustrating being unable to influence the AI's control of inaccessible inputs. This theme illustrates how participants learned to cooperate with their AI partners.

P5 understood what her AI partner was doing, but found that even predictable AI can be difficult to play with. The two participants who noticed the presence of automation had difficulty playing the game when the agent did not do what they wanted. This was not a question of understanding the split of control (as in the previous section), but a problem of coordinating with an agent that at times performed undesired actions. P5 said: "*I'm just not used to playing games like that. So, for me to wrap my head around it it took a little bit more time.*" Although playing with automation was confusing initially, P5 was able to figure it out. "*I was trying to wrap my head around trying to control it better. So, it was just kind of difficult for me to grasp that in a sense. But then once I did and kind of play around with it and realize how I could control it a little bit better then it was more fun.*" (P5) Even when players understand how automation affects their avatar's activities, they may still have difficulty using this inert knowledge.

P6 did not understand what the AI agent was doing, so he found that ambiguity makes sharing control frustrating. P6 was unsure which of his avatars' activities were under his control. While playing *Dino Dash*, he tried to influence the dino's direction by tilting the bite switch. "*I think* [it was frustrating] *just not fully understanding the physical trick to the game. Like how to do things.*" (P6) His confusion about the games' control responsibilities increased the time for him to learn to play effectively: "[The frustration] *wasn't anything major. It just was something that I figured out and moved on from.*" (P6) Despite his difficulty, P6 believed he could have more control over the game with more experience. Players who cannot recognize how their actions affected the game's outcome may become frustrated when that outcome is not favorable.

The accessibility approaches used in our study enabled participants with vastly different abilities to play the same games using controls personalized to their abilities. They enjoyed leveraging their expertise using familiar devices, but also believed that play may be better for others with abilities they lacked. Partial automation made the games accessible to participants with more profound motor impairments by providing inputs that they could not control themselves. However, this made it more difficult for some participants to recognize how their actions affected the avatar's behaviour and learn to cooperate with their AI partner.

8 DISCUSSION

We have shown how partial automation can enable players with very different physical abilities to play the same games. As presented in section 6, all participants in our study were able to engage in all important aspects of playing the games, answering our primary research question of whether partial automation makes *Dino Dash* and *Dozo Quest* more accessible. Our analysis of participants' interviews answers our secondary research question (i.e., what is it like to play with automation?) and indicates that participants liked the increased accessibility and personalization that partial automation affords. Participants valued playing with devices that they found familiar and empowering. However, they said that being required to play the game differently from others could make them feel disabled. A minority of participants experienced *automation confusion* that made understanding the AI's behaviour and coordinating with it more difficult.

In this section, we discuss two broad areas arising from this work. First, we return to the ontology of accessibility techniques for games, as presented in Section 3. We discuss how accessibility techniques were successfully combined in *Dino Dash* and *Dozo Quest*. Second, we dive into the questions of automation confusion first raised in Section 7.2, showing how two models of interaction (Game Interaction Model [101]; Norman's mental models [74]) help explain the confusion that arose, and presenting potential techniques for mitigating this confusion.

8.1 Broad Accessibility Through Combining Approaches

In Section 3, we presented a novel ontology of techniques for improving game accessibility. The ontology illustrates how these techniques can be combined to make games more broadly accessible. We saw that games designed according to *universal design* principles can be broadly accessible, but are ultimately limited to a specific population, while *interface adaptation* and *player balancing* can make games accessible to players with specific abilities, but cannot support players who lack those abilities. All of these approaches can be combined to make games more accessible than any one approach can on its own. When partial automation is added as a technique, the use of an AI agent extends accessibility to players who cannot control input devices at all. In this section, we discuss how the accessibility approaches used in our study shaped participants' experiences. We specifically discuss the important role of interface personalization to complement partial automation, and the potential of technology developed to support partial automation in improving balancing techniques.

8.1.1 Interface Personalization. While the *Dino Dash* and *Dozo Quest* games were created using universal design, they were unplayable by four of our six participants in their original form. To make the games playable to these four, personalization was required. Alternative devices (Interface Adaptation in Figure 2) allowed two participants to control inaccessible inputs, and partial automation was used by four participants.

Alternative devices helped P5 and P6 to be able to play. P6 would not have been able to play all had the bite switch not been available as an alternative to the standard game controller's face button. P5 was able to control both Direction and Action inputs only because of the availability of a larger joystick and the bite switch. These participants' experiences show that alternative interfaces can help reduce the need for partial automation, allowing players to control inputs that would have been inaccessible with stock hardware.

Our thematic analysis showed that the availability of alternative interfaces goes beyond simply providing accessibility. Players valued being able to use controllers that they find familiar, and felt a sense of accomplishment in being able to make use of their prior knowledge (Section 7). For example, P5 noted that the joystick she used to play the games was similar to the joystick on her power wheelchair, which made her personalized hardware interface immediately familiar. This enabled her to transfer her wheelchair skills to playing the games. Similarly, P6 said that playing with his power wheelchair controls would be better than using an unfamiliar interface. While playing *Dino Dash*, he tried to control the dino's direction by tilting his head, similarly to how he controls the movement of his power wheelchair. When possible, therefore, games should allow players to use their own devices. Familiarity enables players to leverage their experiences of using other devices in daily life, possibly enhancing players sense of accomplishment.

8.1.2 Trading Control is a Form of Player Balancing. Our two example games did not use player balancing techniques, although our study illustrated that these techniques would have been helpful for at least one participant. Player balancing, as presented in Section 3, is used to adjust the difficulty of a game to a player's abilities. In games where partial automation has been implemented, the AI agent could be used to implement a powerful form of player balancing based on *trading control*.

Partial automation requires a hard split of responsibility between the player and the AI agent. For a given input type, either the player is in charge, or the the AI. But a player may be able to control an input some or even most of the time, yet be unable to use it to overcome particularly challenging sections of a game. The player may prefer to be assisted in specific situations rather than turning control over to the AI for the entire game. Players may prefer to trade control, as described in Section 3.3, by retaining control of all inputs while the AI observes and contributes as necessary.

As a concrete example, P2 played *Dozo Quest* using both the viva2 and the gamepad. He was unable to control the analog stick with his thumb, so he pinched it between his thumb and index finger. This worked for him in most situations, but during his interview he told us that at one point he got stuck. He said: "*There was the stone walls, and you have to jump from stone to stone, and there was the saw blades at the bottom. It was hard for me dexterously to actually get over with the toggle to jump. That was frustrating.*" He said that he was never able to overcome this challenge, and had to use a shortcut to bypass this section. "*That made me focus more on the fact of my deficiency, as opposed to enjoying the game.*" (P2) AI assistance might have helped him progress through this small section without being disabled by it. He said: "*I kept on just dying, jumping from stone to stone. It was almost as if: 'Oh, crap. I can't do this!' Which is why I stopped playing video games altogether. So, that was a negative. That was definitely a negative.*"

For some players, therefore, there might be benefits to extending the technology developed for partial automation to also provide player balancing techniques based on trading control.

8.2 Next Steps in Partial Automation

This paper has introduced the concept of partial automation to increase accessibility of games to people with radically different abilities, such as arising from spinal cord injury. Our study with six persons with spinal cord injury revealed both positive and negative aspects of partial automation, which we discuss below. We follow this discussion with directions for future work, presenting potential approaches that might further improve the technique.

Over all, participants' experiences with playing games using partial automation were positive. As reported in section 6, all players were able to play all aspects of the games. Participants who had been involved with gaming in the past found joy in the ability to play these games. P2, for example, told us that gaming was a beloved pastime that he had to give up after his injury and that playing *Dino Dash* and *Dozo Quest* gave him back something that he lost. He said "[Accessible gaming] *allows you to think that you can still do something that, to be honest, you never thought that you'd be able to do again.*"

Some participants noted negative aspects of the use of partial automation, as reported in Section 7.2. These included automation confusion (where players are unsure which of the avatar's behaviours are due to their actions), feeling of diminished experience as they realize that other players have more control over the game, and relatedly, feeling of lowered agency. We now discuss these issues, and propose potential solutions to help mitigate them.

8.2.1 Automation Confusion. To better explain automation confusion, we refer to the game interaction model of Yuan et al. [101]. Players first *receive stimuli* from the game, which they use to *determine responses*, and then *provide inputs*. These inputs generate new stimuli, triggering another iteration of the model's steps.

The core goal of partial automation is to allow people to play games even when they cannot provide some of the necessary inputs. Using an AI agent to provide the input can disturb the flow of players' interactions with the game, as they see stimuli which may be a result of the agent's actions rather than their own. Player's attempts to build an accurate mental model of the game [74] are hindered by the decoupling of clear cause and effect. More specifically, sharing control with an AI agent introduces ambiguity into the normally tight correspondence between the inputs a player provides and the stimuli they receive.

For example, P6 tilted his head while using the bite switch as if to direct his dino in the direction he was tilting. His superstitious belief that he could influence the AI's behaviour caused him to misinterpret the stimuli he received – because the AI's actions were close enough to his desired actions, he incorrectly extended his mental model with the belief that tilting his head controlled the direction of his avatar's movement. With only partial awareness of the inputs provided by the AI, players may misinterpret the game's stimuli in ways that made determining a response more difficult. P5's difficulty coordinating with her dino indicates that partial automation can also make determining responses more difficult, even when players understand the game's stimuli. She understood that her dino's movement was driven by something else, but had difficulty determining how to coordinate with it. In these two distinct ways, players' automation confusion may affect their abilities to understand what caused a particular stimulus or to determine how to respond. If it is not addressed, players' confusion may lead to a disabling reduction in agency (e.g. P6's frustration trying to influence his dino's movement) due to disparities between their real and perceived control of the game.

8.2.2 Agency and Diminished Experience. In the context of games, agency has been defined as players' perception that the actions they take (i.e., the inputs they provide) determine the game's outcome (i.e., the stimuli they receive) [79]. When players believe that they can control inputs that they cannot, such as when P6 tilted his head to direct his dino, their sense of agency may be diminished if the outcome is different than expected. This was the most common source of participants' automation confusion, although it did not always reduce players' feelings of agency. P3, P4, and P5 all believed that they were in full control of *Dozo Quest*, despite the Movement input being automated. This was not the case for P6 who became frustrated when his dino ignored his directions. To avoid such misunderstandings, games using partial automation may need to better support players' awareness of the AI's actions.

Statements made by P5 and P6 indicate that the automation itself may also affect players' feelings of agency. P5 recognized that her dino moved of its own volition and said that she would have preferred to control the Movement input herself. P6 recognized that he could not control Movement with the viva2, which he said diminished his experience of play.

Games can bolster players' agency by providing an *illusion of agency*—presenting inconsequential choices as meaningful [79]—however, deceiving players about what inputs they control is easily detected whenever the AI agent performs an action that the player did not expect. We propose two solutions to improving the presentation of the AI agent to the player: improving players' awareness of the agent's actions and intentions, and mechanisms for the player to provide high-level guidance to the agent.

8.2.3 Communicating Awareness of Agent's Actions and Intentions. We left it up to participants to discover how to play using their personalized interface, which caused unnecessary confusion for P5 and P6. They were unsure of what the automation could do, what it was doing from moment to moment, and why it was making the choices it did. This made it difficult for P5 and P6 to determine what they were responsible for controlling and to develop strategies around these responsibilities. Recent guidelines for human-AI interaction recommend that designers make clear what the AI is able to do and communicate information relevant to the AI's context to the player [7]. Fortunately, this sort of communication can work in many ways.

Cooperative communication mechanics, such as those identified by Toups et al. [92], could be used by the agent to share its current actions, intentions, and plans. Supporting mechanics could include emotes, gestures, or context sensitive messages. In *Dino Dash*, the AI could highlight the dino or egg it is chasing and in *Dozo Quest* it could highlight the platform it is trying to jump onto. The resulting improved communication could enable players to both infer the cause of the AI's current behaviour and predict its future behaviour.

Communication between humans engaging in cooperation has been extensively investigated in the context of *awareness widgets* for groupware [45, 48] and more recently for games [13]. Stach et al. found that *information-rich embodiments*—awareness widgets that communicate salient information about game characters using glyphs—enabled players to develop better strategies in a *Spacewar!* [81] clone [88]. It may be that information-rich embodiments could also enable players using partial automation to better understand the AI agent.

As explained by Gutwin et al., awareness widgets correspond to one or more *elements of workspace awareness* [46, 47]. Personalized icons might indicate *identity*—"*who is in the workspace?*"—while color-coded carets indicate *authorship*—"*who is doing that?*". Our participants' feedback indicated that players sharing control with an AI agent may have their own set of questions they need answered. They wanted to know what parts of the game they could control, what parts the AI could control, and why the AI was doing what it was doing. It may be possible to answer all of these questions, and any more that arise, using cooperative communication mechanics, information-rich embodiments, and awareness widgets.

8.2.4 Guiding the Agent's Behaviour. A deeper problem is that players may feel disabled by the inability to control automated inputs, especially when it becomes apparent that other players do have control over those aspects. A design challenge is whether it is possible to provide more limited forms of control so that the decision between player and AI control is not completely binary. For example, gaze control could be used to allow players to specify the general direction of movement they would like their avatar to take. Rather than control the game directly using gaze, *implicit interaction* techniques could be used to guide the AI by inferring the player's intentions and desires for its actions [95]. This approach was used by Munoz et al. to train multilayer perceptrons to play *Infinite Mario Bros.* [77] by observing players' gaze alone [72]. Games using partial automation may be able to provide players a greater degree of influence over the AI agent's behaviour by augmenting their control with high-level, gaze-based guidance.

Guiding the agent's behaviour could take other forms as well. Interactive machine learning could enable players to further personalize partial automation by correcting or critiquing their AI partner's behaviour [6]. In particular, players could reward or punish their agent according to the desirability of its actions using interactive reinforcement learning. Over time, the player's feedback could improve the agent's behaviour, as was shown by Thomaz et al. who found that players were able to teach a game-playing agent to follow a recipe in a cooking game [90, 91]. This form of interaction could augment players' influence over their partner, improving its coordination with their playstyles, using as little as one or two additional buttons.

9 LIMITATIONS

Our study found that partial automation can make the same game accessible to players with radically different abilities; however, this conclusion was drawn from a small sample of participants, games, and forms of control sharing. We asked four participants, all of whom have spinal cord injury, to share control of two games, by delegating control of their Movement or Direction inputs. Due to the vast differences in these participants' physical abilities, this provides solid evidence that partial automation can make games more broadly accessible. However, further study is required to determine how these results extend to different kinds of games.

Participants were not told explicitly about partial automation. Their comments therefore explained their experiences (positive and negative) in *using* partial automation, but did not address the *concept* of partial automation. We argue that this was the correct approach for this first study, as it was important to understand players' experiences without having primed them to expect a particular type of interaction. Further studies would nevertheless be interesting in which partial automation was revealed a priori to allow participants to discuss the idea itself.

10 CONCLUSION

We have presented partial automation, a novel approach to personalizing control of games to the physical abilities of individual players. Under this approach, players control the aspects of the game that they are capable of controlling, and an AI agent controls the game's other inputs. An exploratory study involving people with spinal cord injury indicates that partial automation makes existing games more broadly accessible by personalizing control for players with vastly different abilities. All of the study's participants were able to play the same games, which may have been impossible otherwise.

Partial automation is complementary to and can be used with other approaches for increasing accessibility in games. Results from our study, including feedback from participants, indicate that partial automation can overcome shortcomings inherent to these other approaches but also that each approach can complement the others. Interface adaptation enabled participants to maximize their control using familiar controllers and player balancing may have helped players to overcome situationally disabling challenges. When combined, universal design, interface adaptation, player balancing, and partial automation can make games accessible to players with vastly different physical abilities.

Partial automation can, however, lead to confusion, particularly if the player is uncertain as to what parts of the game are under their control and what parts are not. Participants found it difficult to coordinate with an AI partner whose behaviour they did not understand. Cooperative communication mechanics, information-rich embodiments, and awareness widgets may enable players to better coordinate with the AI. Gaze control and interactive reinforcement learning may provide players a means to guide their partner's behaviour. Future work in this area will be devoted to exploring how to convey to players the nature of the shared control between the player and the AI agent.

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