Astrojumper: Motivating Exercise with an Immersive Virtual Reality Exergame

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Astrojumper: Motivating Exercise with an Immersive Virtual Reality Exergame

Abstract

We present the design and evaluation of Astrojumper, an immersive virtual reality exergame developed to motivate players to engage in rigorous, full-body exercise. We performed a user study with 30 people between the ages of 6 and 50 who played the game for 15 min. Regardless of differences in age, gender, activity level, and video game experience, participants rated Astrojumper extremely positively and experienced a significant increase in heart rate after gameplay. Additionally, we found that participants' ratings of perceived workout intensity positively correlated with their level of motivation. Overall, our results demonstrate that Astrojumper effectively motivates both children and adults to exercise through immersive virtual reality technology and a simple, yet engaging, game design.

1 Introduction

The use of video games in physical exercise, known as exergaming, has been increasing in attention and popularity in recent years (Sinclair, Hingston, & Masek, 2007). The release of commodity motion sensing devices, most notably the Nintendo Wii remote and Wii Fit balance board, has resulted in a large number of video games that use body motion as a game mechanic. While video games can be effective motivators, we believe that using immersive, stereoscopic virtual reality (VR) will provide an even greater incentive for physical activity. To this end, we developed Astrojumper, a virtual reality exergame that was designed to study the benefits of stereoscopy and immersion for motivating physical exercise in both children and adults (see Figure 1).

The input devices used with commodity gaming platforms (e.g., balance boards, dance pads, and accelerometer-based controllers) are generally not capable of sensing motions with six DOF, which makes it difficult to measure whether a game engages the user's entire body, including the head, torso, and limbs, in physical activity. Locomotion interfaces such as bicycles have also been used for exercise games (Mokka, Väätänen, Heinilä, & Välkkynen, 2003), but the interactions that can be performed with these devices are limited. In contrast to these interfaces, Astrojumper tracks the user's head, torso, and arms in 3D space, which allows us to support full-body activities such as dodging, ducking under, jumping over, and grabbing virtual stimuli.

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Figure 1. *A user playing Astrojumper in our three-wall stereoscopic projected display. Gameplay requires rapid body movements to dodge planets and collect bonuses. During a UFO attack, the player can execute quick arm motions to throw green laser beams at the enemy spacecraft.*

As quickly as new input devices are created to facilitate exercise in games, players discover ways to win without actually exercising. For example, while the Nintendo Wii allows players to engage in realistic motions such as swinging a tennis racket, it does not require accurate and realistic behavior, as frustrated players observe when they are beat by an opponent moving only their wrists while sitting on the couch. One way to prevent players from finding workarounds is to immerse them in virtual reality and tie game performance to actual, full-body activity. Astrojumper was designed and developed so that players must move not only their feet and legs, but must also engage their upper body to win the game. This is a key component to all games with a secondary purpose: the purpose must be central to the core game mechanic, in other words, the activity that players engage in more than any other. Balancing a game's purpose with fun is challenging, requiring game designers to focus on how to achieve gameflow while engaging players in the main purpose of the game. Astrojumper achieves this balance by requiring full-body motion to play, which encourages exercise, while adapting the game to player performance, becoming more challenging as players excel or slowing down as players make mistakes.

In this paper, we report on a user study that was conducted to evaluate Astrojumper's effectiveness in motivating players to exercise. In addition to investigating whether Astrojumper is fun and effective in promoting exercise, we also intended to gather feedback for the design of immersive exergames. While the average gamer does not yet have access to a virtual reality setup at home, recent technological advances may make this possible in the near future. For example, monitors, plasma displays, and projectors with refresh rates over 120 Hz are now available and can be combined with the NVIDIA 3D vision kit to provide stereoscopic 3D gaming on a desktop PC. Furthermore, the success of the Nintendo Wii has spurred innovation for commodity motion sensing devices across a variety of platforms. Given the increasing accessibility of immersive technology, we believe that it is important to study the benefits of using virtual reality for emerging applications such as exergaming.

2 Related Work

Though exergaming has seen a recent increase in popularity, few guidelines have been developed for the design of these applications. Furthermore, several evaluations of previously developed games have cited problems in finding the balance between engaging gameplay and appropriate levels of physical exertion. For example, Kick Ass Kung-Fu is a fitness game that was designed to engage adults involved in martial arts (Hämäläinen, Ilmonen, Höysniemi, Lindholm, & Nykänen, 2005). Participants were able to use their physical actions to move an avatar on a large projection display to fight virtual competitors. While the results of this study indicated that the game was effective for motivating martial arts and acrobatics training, users complained that the game design limited how they were able to interact with the system, and that they were not able to perform the moves they wanted. Luke et al. evaluated the Sony EyeToy, a full-body exertion interface, to analyze energy expenditure in a variety of exercise games (Luke, Coles, Anderson, & Gilbert, 2005). While he found that this system was engaging, he concluded that the system's effectiveness was limited due to only small bursts of exercise followed by long pauses that did not allow the player's heart rate to build. Similarly, in a personal analysis of three video game exertion interfaces, Smith found similar problems with the Cateye GameBike, and noted that he was unable to maintain his target heart rate due to the long load times between races (Smith, 2005). He also found that he was unable to get a full workout from just a single game, and concluded that exergames should consider in-game warm-ups and cooldowns, as well as dynamic difficulty adjustment.

Over the past few years, children have been spending more time engaging in screen-based activities such as watching television, playing video games, and using computers, possibly leading to an increase in childhood obesity (Marshall, Gorely, & Biddle, 2006). Because of this, exergames designed specifically for young children have been developed (Höysniemi, Hämäläinen, Turkki, & Rouvi, 2005; Bekker, van den Hoven, Peters, & Hemmink, 2007; Yannakakis, Hallam, & Lund, 2006). Research that evaluates game design specifications for this population indicate that children enjoy realistic fantasies and sportlike activities that require physical dexterity, balance, coordination, and strength (Acuff & Reiher, 1997). Additionally, work that specifically evaluated exergame requirements for children suggested that these systems should provide robustness, responsiveness, intuitiveness, and physical appropriateness to ensure the children would be able to effectively engage with the game (Höysniemi et al., 2005). These principles have since been put into practice in developed systems for children, such as in Bug-Smasher, developed by Yannakakis et al. (2006). Bug-Smasher uses a 6 × 6 platform with randomly appearing colored lights to get children to jump around and smash the presented lights (or *bugs*). Children found the game quite enjoyable, and Yannakakis also reported that children who were able to project their own fantasies into the game world had higher levels of enjoyment. Bekker et al. developed two additional systems based on these presented game specifications: Flash Poles and Battle Bots (Bekker et al., 2007). Both of these game systems were designed to allow for more open-ended exergame play, with Flash Poles allowing the children to interact with physical poles that provided light feedback and Battle Bots allowing the children to control tanks with their body movements. Early user studies on elementary school-aged children were performed on both of these systems, and though no quantitative information regarding exerted physical activity was reported, the children seemed to find the systems both engaging and effective at promoting social relationships between active participants. In addition to games employing platforms or physical props, Hoysniemi et al. developed a computer-vision based game that allows children to control a 2D dragon, QuiQui, on a screen using various body movements (Höysniemi et al., 2005). The experimenters found that most of the movements were intuitive for the children to perform, and that this was an important aspect of game play. The authors also suggest that future exergaming work look into developing systems that allow for more holistic full-body movements, such as jumping, which we took into consideration in the design of Astrojumper.

Research has also been performed to evaluate the effectiveness of exergames at promoting social relationships, yielding positive results. For example, Mueller et al. describe three exergames designed to study social interaction (FlyGuy, Push N' Pull, and Breakout for Two), and found that games involving physical activity augmented social relationships better than traditional multiplayer computer games (F. Mueller, Agamanolis, & Picard, 2003; F. F. Mueller, Stevens, Thorogood, O'Brien, & Wulf, 2007). Additionally, Nautilus is a cooperative game requiring players to free a virtual dolphin through physical gestures such as clapping, stomping, and flapping (Strömberg, Väätänen, & Räty, 2002). However, for these games, few considerations were given to promoting physical exertion, and instead focused on engaging cooperative play.

Exercise technology has also been shown to be effective in rehabilitation and training. Virtual reality exercise systems have been shown to improve cognitive function in people with neurological injuries on a variety of memory and cognition tasks (Grealy, Johnson, & Rushton, 1999). In two case studies performed by Kizony et al., virtual reality technology was used to improve balance and coordination of a patient in a wheelchair and a patient recovering from a right hemispheric stroke (Kizony, Katz, & Weiss, 2003). Because these VR systems are typically quite expensive, research has been done to examine the effectiveness of low-cost rehabilitation systems. Pilot studies were performed by Rand et al. in 2004 to compare an expensive VR system to a Sony Eye Toy (Rand, Kizony, & Weiss, 2004). In healthy young adults, there was no difference in presence, enjoyment, or motivation between these two systems. In healthy older adults and older adults recovering from stroke, the results were unclear, as each of these measures varied greatly based on the type of game played on each system. In 2008, these experimenters performed a similar study, concluding that the Sony Eye Toy may be an effective low-cost tool to engage patients recovering from a stroke in physical activity (Rand, Kizony, & Weiss, 2008). The authors note that there are certain technological limitations in the Eye Toy, such as an inability to systematically report a user's performance, which may make it difficult to use as a therapeutic tool. Regardless, the authors conclude that the Sony Eye Toy was easy to operate, was enjoyable, and generated a high sense of presence, making it effective overall. Morrow et al. replicated an expensive system for stroke rehabilitation using a much more low-cost system as well, showing that it was possible to create similar applications with reasonable costs (Morrow, Docan, Burdea, & Merians, 2003). However, the authors acknowledge their low-cost system has less functionality than the original, and suggest that user testing be performed to evaluate how this decrease in functionality affects the system's effectiveness as a rehabilitation tool. In addition to rehabilitation, virtual reality has also been used for training physical movements in virtual environments, such as tai chi (Chua et al., 2003). While these studies do indicate that VR is effective for engaging users in physical activities, they focused primarily on achieving a specific task, with no emphasis on motivating game design factors.

Overall, in studies that have compared the differences between VR-aided exercise and nonaided exercise, it has been shown that VR resulted in less intense physiological responses to pain due to extended physical activity (Chuang et al., 2003). Similar results were also found by Porcari et al., who evaluated the effects of virtual simulation on exercise motivation and intensity while pedaling an exercise bike (Porcari, Zedaker, & Maldari, 1998). The experimenters found that participants who were provided with a virtual environment had higher heart rates and burned more calories than the participants without this virtual simulation. The benefits of virtual reality exercise even extend to participants' moods, with participants who participate in VR-aided exercise being significantly less tired and showing significantly more enjoyment than those who engage in standard exercise (Plante, Aldridge, Bogdan, & Hanelin, 2003). Additionally, previous research suggests that increased immersion (over less immersive virtual reality) is even more beneficial for enhancing a user's motivation in exergames. For example, recent work by IJsselsteijn et al. shows that when the visual display appears to be more realistic and immersion is higher, participants were more motivated to engage in exercise (IJsselsteijn, Kort, Westerink, Jager, & Bonants, 2006). These results also show that spatial presence, engagement, and ecological validity were also higher for increased immersion. This work suggests that more immersive virtual environments will heighten the enjoyment the user is experiencing, and thus will have a beneficial effect on the user's motivation to engage in exercise. Increased immersion can also be achieved through stereoscopic projection displays, with a foundation of work indicating that stereoscopy greatly increases presence (Hendrix & Barfield, 1995) as well as task performance (Gruchalla, 2005). To the best of our knowledge, Astrojumper is the first exergame using an immersive stereoscopic display to be formally evaluated.

Given that many previous exergames may not provide the optimal balance between engaging gameplay and physical exertion, it is vital to consider a variety of gameplay factors which may affect the player's psychological and physiological responses. To outline the components of successful video games, Sweetser and Wyeth presented the gameflow model, which emphasizes the importance of the following criteria: concentration, challenge, player skills, control, clear goals, feedback, immersion, and social interaction (Sweetser & Wyeth, 2005). Applying this general gameflow model specifically to the design of exergames, Sinclair et al. suggested

(a) (b)

Figure 2. *(a) When playing Astrojumper, the user needs to dodge planets that are speeding toward him or her. (b) The user can accumulate score multipliers by tapping gold suns that appear periodically.*

a dual-flow model that balances the psychological flow of gameplay (attractiveness) and the physiological flow of exercise (effectiveness) (Sinclair et al., 2007). Putting these models into practice, we carefully considered Sweetser's gameflow criteria during the design of Astrojumper. Additionally, to balance the dual flow of gameplay, Astrojumper adjusts the difficulty level dynamically based on the player's performance. This gameplay mechanic ensures the exercise will be appropriate for players of varying physical fitness, and also supports an individual player's skill development over time.

3 Astrojumper

Astrojumper is an immersive virtual reality exercise game developed for use with a stereoscopic projection display and full upper-body motion tracking. In this section, we describe our gameplay design and the virtual reality setup used to evaluate the game.

3.1 Game Design

In Astrojumper, the user flies through an immersive, stereoscopic outer space environment in first-person perspective and must swerve around, duck under, and jump over the virtual planets that are speeding toward him or her (see Figure 2[a]). The user wears trackers on the forehead, wrists, and waist, which are used to calculate body collisions with the virtual objects. A base of one point is awarded per second, and the player can tap gold suns to gain bonus score multipliers which increase the amount of points earned per second (see Figure 2[b]). If any part of the users' tracked body collides with a planet, their score is frozen for 2 s, with multiple planet collisions resulting in a score freeze for up to 15 s. Collisions also eliminate any score multipliers the user may have collected. If the player is currently in a score freeze, bonus objects will reduce the freeze by 2 s; otherwise, the player will gain 30 points in addition to adding to the score multiplier. Periodically throughout the game, UFOs appear and begin shooting red laser beams at the location of the player's head. The player needs to dodge these beams, and can shoot green lasers by making strong throwing motions with an arm until the UFO is defeated. Music was played throughout the game session, since this has been shown to be important for promoting the enjoyment of exercise (Winniger & Pargman, 2003).

Because people are encouraged to engage in exercise multiple times per week (American College of Sports Medicine, 2000), replayability is an important factor in the design of exergames. If too repetitive, exergames may run the risk of boring their users, or not providing the necessary motivation for individuals to play the game often enough to result in appreciable health benefits. Additionally, the American College of Sports Medicine suggests engaging in cross-training activities which vary the type of physical motion performed during exercise. For both of these reasons, we embraced the idea of using laser beams and bonus planets in our game design. Without these features, the movements users are encouraged to perform would be somewhat limited to jumping side to side, ducking, and swerving to avoid the planets. However, the addition of bonus planets that were meant to be grabbed engaged the users' bodies in more diverse ways, allowing for stretching and reaching. Allowing the player to periodically shoot laser beams by making throwing motions also increased the exercise diversity provided by Astrojumper, making it possible for the user to get an arm workout as well. While providing a more diverse exercise environment, these features also diversify the game as a whole, perhaps improving the overall replayability. Though no formal data were collected during early testing studies, preliminary versions of Astrojumper that did not include these features were criticized for being too repetitive. After the addition of bonus planets and lasers, this criticism became significantly less common.

Providing feedback to the player was an important focus in the design of Astrojumper. Following Sweetser's gameflow model, we provided clear notification of events such as collisions and bonuses using colored text, sound, and particle effects. Pop-up text notified participants of which body part had collided with a planet, allowing them to be more conscious of the positions of their limbs. More generally, the heads-up score display also changed color to reflect the participant's current performance, with a score printed in green indicating the player was doing well, and a score printed in red meaning the player is currently frozen.

Following the American College of Sports Medicine's guidelines for exercise (American College of Sports Medicine, 2000), a complete game session of Astrojumper follows three phases: warm-up (15%), exertion (70%), and cooldown (15%). During the warm-up session, the planets move very slowly and gradually build up to a more challenging speed during the exertion phase. The speed slows down again for the cooldown phase, allowing for a gradual decrease in physical effort. Though game sessions may last any amount of time, for our evaluation in this paper, we used a total game time of 15 min (2.25 min warm-up, 10.5 min exertion, 2.25 min cooldown).

Putting Sinclair's dual-flow exergame model into practice and following the suggestion of Smith et al. (2005), Astrojumper's difficulty level adjusted dynamically throughout the game. To make sure that Astrojumper would be playable for users at all levels of physical fitness, Astrojumper begins very slowly, providing all users with a warm-up phase. After this phase is complete, planets will begin to gradually come out at a slightly faster rate. If the player is successfully able to avoid these planets, the speed will continue to increase. If the player starts to collide with the planets, their speed will reduce. This back-and-forth adjustment finds a speed where the player can successfully avoid almost all of the planets, and will continuously update throughout the game. To calculate this within our game, we collect information about how well the player is doing every 3 s as a percentage that indicates how many planets they avoided out of all presented planets. If this calculated percentage gets lower each time it is calculated, it indicates that the game is too difficult, and the stimuli will slow. If the percentage stays the same or gets higher, the planets will increase in speed. This design is in line with the dual-flow model, which suggests that gameflow needs to be balanced between too easy (boring) and too difficult (frustrating).

3.2 VR Setup

We deployed Astrojumper on a three-sided immersive projection display with $8' \times 6'$ rear-projected screens. Two Barco Gemini stereoscopic projectors were used for each screen, and circular polarized glasses were worn on the user's head. A Polhemus Fastrak electromagnetic tracker was attached to the user's glasses, and two trackers were enclosed within sweatbands on the user's wrists (see Figure 3). The users wore a small backpack to guide

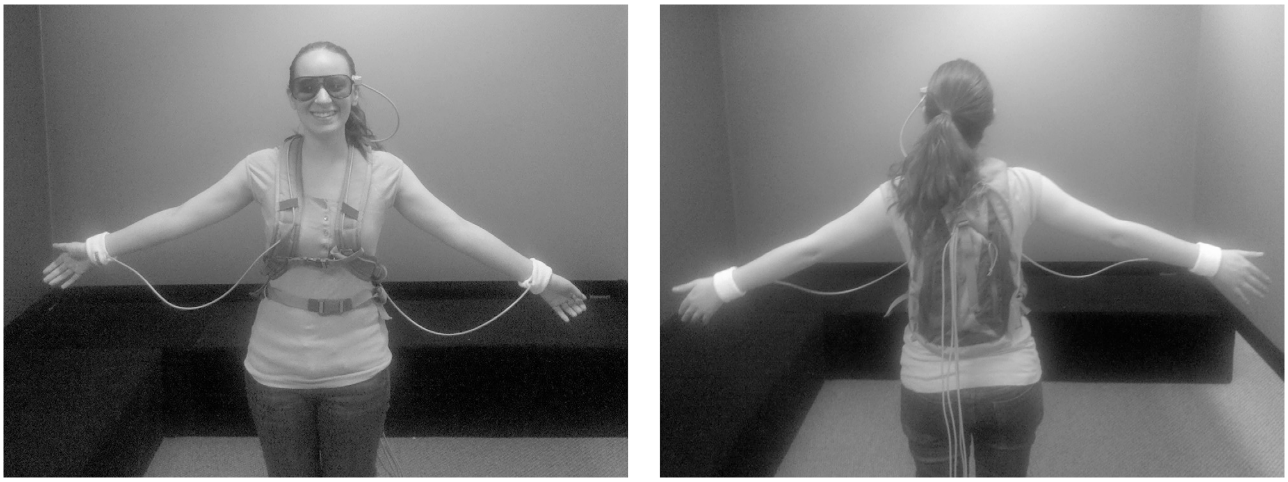

Figure 3. *Users wore a small backpack to guide the tracker wires around the body, allowing them to move freely without without getting tangled.*

the tracker wires to each tracked portion of the body, allowing the user to move freely without getting tangled. A fourth tracker was attached to the bottom of the backpack to track the user's waist.

Astrojumper was run on a single Intel Core i7 3.33 GHz PC running Windows 7 64-bit with 12 GB of RAM and three NVIDIA GTX 260 graphics cards, each of which provided output for a single projector. The game was implemented using the osgVirtualEnvironment engine, which is an open-source engine built on top of OpenSceneGraph 2.8.0. Graphics were modeled in 3D Studio Max, and were rendered in stereo at 60 frames per second. Audio was provided through OpenAL, and tracker communication was accomplished using the virtual reality peripheral network (Taylor et al., 2001). Astrojumper's engine is dynamically configurable, which allows us the capability of deploying the game on different hardware on the fly (e.g., head-mounted displays, stereo plasma displays, portable projection-based setups, etc.).

4 Evaluation

Thirty people participated in the study (19 male, 11 female) ranging in age from 6 to 50 ($M = 21.17, SD = 9.53$). Ten participants were children (ages 6–17) and 20 were adults (ages 18–50). Participants were recruited primarily via word of mouth and were not limited to university students. All participants were told the study would require exercise, and that they were not eligible to participate if they had a medical condition which prohibited voluntary physical exertion.

4.1 Procedure

4.1.1 Stage 1: Preexperiment. Participants were invited to come to the UNC Charlotte Visualization Center one at a time for a total of 45 min. First, they were asked to read and sign an informed consent form and were given the opportunity to ask questions about the VR equipment and the study. We explained that we were evaluating how people interacted with an exercise game, though to reduce demand characteristics, the participants were not told we were specifically looking at motivating factors. After the consent form was signed, we attached a HeartMath emWave Desktop heart rate monitor to the participant's earlobe to obtain their resting heart rate. We allowed the system to calibrate for 30 s, and then calculated the average heart rate over 2 min. Participants were then given a prequestionnaire to gather demographic information, activity level, exercise motivation, and video game habits.

4.1.2 Stage 2: Astrojumper. Participants were led to the immersive display and were shown how to put on the backpack and trackers. Astrojumper's virtual world was displayed on the walls, allowing the participants some time to adjust to the 3D stimuli before the game started. At this point, we explained the rules of the game to the players and showed them how to react to the various types of virtual objects they would encounter. We allowed participants to ask any questions they had, and then started the 15 min game session when the players were ready. During the game, we held the wires approximately 6 ft behind the participants to ensure they would not trip, and did not communicate with them unless they asked us a question about the game.

4.1.3 Stage 3: Postexperiment. After the session was finished, we instructed participants to remove the backpack, and then calculated their exerted heart rate as was done previously. Next, the participants were asked to fill out a postquestionnaire which included free-response questions and questions related to workout intensity, motivation, and gameflow. After completing the questionnaire, participants were debriefed and the experiment was concluded.

4.2 Measures

4.2.1 Heart Rate. True resting heart rate is typically measured by taking a heart rate reading for several mornings in a row before a person gets up from bed. However, since collecting this rate was infeasible for this study, we used a proxy measure for resting heart rate at the beginning of our study. We used a HeartMath emWave Desktop heart rate monitor to measure the subject's resting heart rate (in beats per minute) before game play and exerted heart rate immediately after the Astrojumper game session. We also calculated the exerted heart rate as a percentage of each participant's estimated maximum heart rate, which is frequently used for estimating the target heart rate recommended to receive the benefits of physical exercise (*American Heart Association: Target Heart Rates*, 2010). We estimated the maximum heart rate using the following formulas based on the participant's age and gender: $205.8 - 0.685 \times age$ for males (Robergs & Landwehr, 2002) and $206.0 - 0.88 \times age$ for females (Gulati et al., 2010). It should be noted that since the gameplay session included a cooldown phase, the heart rate after the session would have dropped from the peak levels that occurred during gameplay. We attempted to collect heart rate information during the exertion phase, but we were unable to obtain valid readings using this monitor due to participants' rapid physical movements. Regardless, the differences in percentage of maximum heart rate before and after gameplay still gives us an objective, albeit conservative, measurement of participants' physiological reactions to the physical activity required to play Astrojumper. While a significant rise in heart rate would imply that they had engaged in strenuous exercise, no change in heart rate would indicate that either Astrojumper gameplay did not require enough exertion or that participants were not sufficiently motivated to engage in physical activity.

4.2.2 Workout Intensity, Motivation, and Gameflow Evaluation. Participants were asked to subjectively rate their workout intensity on a 7-point Likert scale (1 = "not at all intense" to 7 = "extremely intense"). This was done to assess the perceived level of intensity of their exercise during the game session.

To gauge the motivation potential of Astrojumper, participants were asked to complete eight questions pertaining to their level of motivation. This series of statements were evaluated using 7-point Likert scales (1 = "strongly disagree" to 7 = "strongly agree"). Some questions on this survey included "I would rather do game-based exercise over typical exercise," "I put more effort into my movements than I would have if there wasn't any virtual simulation," and "I would exercise more if I could play Astrojumper whenever I wanted." The ratings from individual questions were averaged together to calculate the motivation score.

To assess Astrojumper's gameflow, participants were also presented with eight gameflow components from Sweetser's model and asked to rate (1) how present these characteristics were in Astrojumper, and (2) how present these characteristics should be in exercise games in general. Ratings were collected using a 5-point scale of importance (1 = "not at all," 2 = "somewhat," 3 = "moderately," 4 = "mostly," 5 = "completely"). For each gameflow component, we calculated a gameflow score by dividing the Astrojumper rating by the ideal exercise game rating. The resulting percentage represents the degree to which Astrojumper met participants' gameflow expectations for exercise games. It should be noted that a score may be over 100% if Astrojumper were rated higher in a particular category than the general exercise rating. To produce an overall gameflow evaluation score that represents the degree to which Astrojumper fell short of participants' gameflow expectations, we capped the individual gameflow component scores at 100% and then averaged them. By considering only the differences where Astrojumper was rated lower than the ideal exergame, we avoided an aggregated score that was potentially misleading.

4.2.3 Video Game and Exercise Habits.

We provided participants with a preexperiment questionnaire that gathered their basic demographics, video game experience, and exercise habits. For video game experience, participants were asked to rate the degree to which they enjoy playing video games on a 7-point Likert scale, with higher numbers corresponding to greater video game enjoyment. Participants were also asked to classify themselves in one of four gaming categories ("nongamer," "casual gamer," "moderate gamer," "hardcore gamer").

To gather how active our participants were, we used the Godin Leisure-Time Exercise Questionnaire, a short survey that collects how many times in a typical week the subject engages in mild, moderate, and strenuous physical activity, with a greater weight applied to more strenuous exercise (Godin & Shephard, 1997). As described by Godin and Shephard, these three components were then combined to calculate an overall score that indicated how active our participants were, with higher numbers corresponding to greater amounts of overall physical activity. We also administered the motives for physical activity measure to gauge our participants' motivations for choosing to exercise (Ryan, Frederick, Lepes, Rubio, & Sheldon, 1997). Participants were provided questions regarding five distinct possible reasons for exercising: interest in a particular sport, wanting to gain skill or competence at an activity, desire to improve fitness or health, desire to appear more attractive, and desire to achieve benefits of social interaction, such as playing a sport with a friend. Participants were presented six statements relating to each of these five components, and were asked to rate their agreement with the statement on a scale from 1 ("strongly disagree") to 5 ("strongly agree"). Overall motivation for each component was calculated by averaging the scores for the six related statements within each category. These two exercise questionnaires allowed us to gauge not only the frequency of our participants' exercise, but also the underlying motivations behind their reasons for engaging in physical activities.

4.2.4 Qualitative Feedback.

After playing Astrojumper, participants were asked to discuss their favorite and least favorite aspects of the game in free-response boxes. They were also given an opportunity to provide general feedback and comments.

4.3 Results

All statistical results reported in this paper use a significance value of $\alpha = .05$.

4.3.1 Heart Rate.

Participants' heart rates (in beats per minute) were treated with a 2 × 2 mixed analysis of variance (ANOVA), testing the between-subjects effects of gender and the within-subjects effect of time (resting or exerted). Participants' exerted heart rates after the cooldown phase ($M = 106.67, SD = 13.75$) were significantly higher than their resting heart rates ($M = 77.07, SD = 13.15$), $F(1, 28) = 98.31, p < .01$, $\eta_p^2 = .78$. There was an overall main effect for gender regardless of the time of measurement, with males experiencing a slower heart rate than females. However, this is a well-known physiological difference between genders (Umetani, Singer, McCraty, & Atkinson, 1998). The interaction effect between time and gender was not significant, $p = .94$.

Table 1 shows a chart of the participants' heart rates before and after exertion, as well as the exerted rate calculated as a percentage of maximum heart rate.

Table 1. *Resting and Exerted Heart Rates*

		Heart rates					Heart rates		
Age	Sex	Resting (bpm)	Exerted (bpm)	Exerted (% max)	Age	Sex	Resting (bpm)	Exerted (bpm)	Exerted (% max)
6	F	81	100	50	20	F	85	122	65
8	F	75	111	56	20	F	89	106	56
9	M	67	75	38	22	F	67	102	55
12	M	65	102	52	22	M	82	100	52
14	M	64	95	48	23	M	92	115	61
14	M	80	110	56	24	M	82	109	58
14	F	118	119	61	24	F	92	118	64
15	M	72	121	62	25	M	62	114	60
15	M	79	91	46	26	F	63	129	70
16	M	73	113	58	27	M	57	120	64
18	M	65	87	45	28	M	94	118	63
19	F	67	100	53	30	M	60	70	38
19	M	86	95	49	31	M	65	103	56
19	F	87	115	61	45	F	84	105	63
20	M	77	119	62	50	M	82	116	67

NOTE. Resting and exerted heart rates were measured immediately before and after the game session, which included a cooldown stage. Playing Astrojumper resulted in an average heart rate increase of 29.6 beats per minute. Additionally, 24 out of 30 participants had exerted heart rates that were within the American Heart Association's target heart rate range for physical exercise (between 50–85% of maximum heart rate) even after this cooldown.

To receive the benefits of physical activity, the American Heart Association recommends a target heart rate between 50–85% of the estimated maximum heart rate (*American Heart Association: Target Heart Rates*, 2010). Even though exerted heart rates were measured after the cooldown phase, allowing then to drop from the peak levels achieved during exercise, 24 out of 30 participants were within this target zone ($M = 56.31\%, SD = 8.05\%$). Additionally, participants' exerted percentage of maximum heart rates were significantly correlated with age, $r(30) = +.44, p = .02$, indicating that older participants tended to experience higher heart rates, even though the heart rate maximum formula had already accounted for age differences.

4.3.2 Workout Intensity, Motivation, and Gameflow Evaluation. The subjective workout intensity ratings (1–7) indicated that participants felt Astrojumper provided a moderate to high level of physical exercise ($M = 5.07, SD = 1.44$). Additionally, participants' motivation scores (1–7) indicated that Astrojumper successfully motivated them to exercise ($M = 5.69, SD = 1.10$). We excluded two participants from the gameflow analysis because they did not understand the instructions, both of whom were young children (ages 6 and 9). The overall average gameflow score also indicated that Astrojumper came close to completely fulfilling participants' expectations for the ideal exercise game on a variety of gameflow characteristics ($M = 90.59\%, SD = 7.13\%$). Figure 4 shows the breakdown of the gameflow rating scores for each of the eight categories.

The relationship between age, motivation, workout intensity, and overall gameflow evaluation score was assessed using Pearson correlation coefficients. There was a significant positive relationship between motivation and workout intensity, $r(30) = +.49$, $p < .01$. The gameflow evaluation score was positively correlated with both workout intensity, $r(28) = +.45$, $p = .02$, and motivation, $r(28) = +.41$, $p = .03$. None of the correlations with age were significant. These results suggest that to design exercise games that provide an effective workout, participants' gameflow expectations and their level of motivation should be considered.

4.3.3 Video Game and Exercise Habits. Our participant pool consisted of seven nongamers, 15 casual gamers, five moderate gamers, and three hardcore gamers. For video game enjoyment ratings (1–7), most participants indicated they enjoyed playing video games ($M = 5.17, SD = 1.15$). Responses on the Godin Leisure-Time activity scale indicated that participants tended to engage in moderate levels of exercise ($M = 53.97, SD = 31.84$), though this varied greatly among participants. The motives for physical activity measure (1–5) rated most important by our participants was fitness ($M = 4.19, SD = 0.82$), followed by interest ($M = 3.49, SD = 0.84$), appearance ($M = 3.33, SD = 1.28$), and competence ($M = 3.28, SD = 1.05$). Social motivations were rated as least important ($M = 2.87, SD = 1.23$).

To assess the potential impact on video game and exercise habits on exercise game design, we computed Pearson correlation coefficients between the subjective ratings of motivation and workout intensity and our measures of video game enjoyment, Godin Leisure-Time activity, and the motives for physical activity. However, none of these factors significantly correlated with the degree of motivation to play Astrojumper or the level of workout experienced by participants. Additionally, none of the video game or exercise habit measures were significantly correlated with age.

4.3.4 Qualitative Feedback. In general, we received extremely positive feedback, and participants cited a variety of reasons for their motivation to play the game. Three of our younger participants said that the game allowed them to pretend they were various superheroes or cartoon characters, with a 12-year-old male participant citing that he enjoyed inventing different "move styles" to change character roles. Two participants mentioned that they most enjoyed the quick thinking and strategy that was required to maximize the score, and an additional four described how much they enjoyed engaging in full-body interaction. Three participants directly compared Astrojumper to the Wii Fit, saying that full-body exercise was much more motivating and effective, one stating it was "much more than the Wii could ever offer."

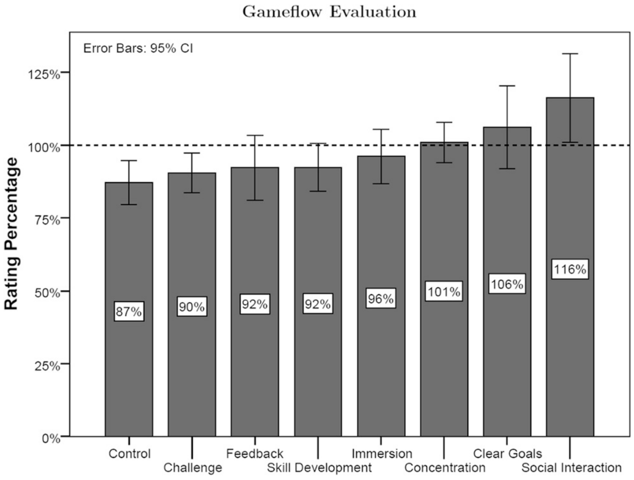

Figure 4. *Participant gameflow evaluation scores were calculated by dividing Astrojumper's rating by the general rating of importance in exergames for each gameflow category. Thus, the percentages represent to the degree to which Astrojumper satisfied participants' gameflow expectations.*

Most participants mentioned specific gameplay aspects of Astrojumper. For example, a 19-year-old male participant wrote:

> My favorite part of Astrojumper was the fact that it didn't really feel like exercise—I wasn't focused on my heart rate or trying to "push" myself. I just played the game. It wasn't until afterwards it had felt like I had done any exercise.

Additionally, a 22-year-old male mentioned:

> I most enjoyed the amount of quick, snap decision movements that were required. It incorporated both top and bottom movements, and this basic sort of game could hone some very sharp coordination skills.

The negative feedback we received was much less varied: out of 30 participants, 17 either left this question blank or wrote that they had no complaints or negative comments. Five participants complained that there were times when they had been penalized for hitting a planet when they felt they were out of its way. This was unavoidable, and was due to inconsistent tracking data that occurred when the electromagnetic trackers were out of range of the emitter. Since the emitter was mounted from the ceiling, this sometimes occurred when participants dropped to the floor to duck under a planet. Three participants said they would have preferred a larger tracking area so they would have some more room to move around, and the other five simply offered suggestions for ways to make the game more fun, such as adding boss fights, additional enemies, or making it easier to beat the UFO.

Finally, we received many positive accolades in the free-comment section. Some responses included: "it was amazing, it should be a real video game I could play whenever I want," "I loved all of it, and would recommend it to anybody," and "This was one of the best games I've ever played. I actually enjoyed exercise!" Additionally, many participants (over half) requested to play the game a second time, and we received many requests from friends of participants who heard about the game, even after the study was over.

4.4 Discussion

As Sinclair's dual-flow model suggests, our results indicated there is an important relationship between gameplay attractiveness (measured by our gameflow evalation) and exercise effectiveness (measured by ratings of workout intensity). These results reinforce the claim that exergames need to be fun and engaging in order to maximize their effectiveness as an exercise tool. Additionally, the relationship we found between motivation and workout intensity supports the basic premise that games can be used to motivate physical activity.

In order to better understand the design of exergames, we investigated the potential influence of personal factors such as video game experience, exercise habits, and reasons for engaging in exercise on participants' motivation and perceived workout. However, regardless of these criteria, Astrojumper received overwhelmingly positive ratings. While we were not able to develop any specific design guidelines, this is a very interesting result, since it suggests that virtual reality exergames may have broad appeal for a wide variety of users. Though participants were strongly motivated regardless of gender or age, we noticed qualitative differences in comments from children and adults. For example, free-response comments from the children in our study frequently mentioned getting "lost" in their fantasy world. This is consistent with a previous exergame study which found that an increase in fantasy level correlated strongly with children's levels of enjoyment (Yannakakis et al., 2006). However, feedback from the adult participants often mentioned being compelled by the challenge and skill required to play the game. Though participants may perceive the game differently, we conclude that immersive virtual reality exergames have strong potential to motivate physical activity in both children and adults, regardless of their video game and exercise habits.

Astrojumper was designed to be rated "*E for everyone*," in that we chose to design a game atmosphere, outer space, which we felt was both gender and age neutral. The consistently high levels of motivation across all of our participants may be attributed to this design choice, as it showed no subculture preference to any subset of our users. Additionally, because Astrojumper's mechanics were not very complex, we had no issues with very young users not understanding the directions, allowing them to enjoy the game as much as older users. To this end, we believe that with careful consideration to game design, it is possible to design exergames that are enjoyable for all users. To ensure that participants would not get bored by repetitive actions, we included opportunities to collect bonuses, gain point multipliers, and designed alternate interaction possibilities within the game. For example, the user can throw an arm forward with a punching motion to shoot a green laser beam at periodically appearing UFOs. This not only kept the game engaging by changing the types of actions the users were performing, but also allowed users to engage more of the body in physical activity, providing an exercise environment which promoted cross-training fitness. Some participants reported that throwing laser beams was one of the most enjoyable aspects of the game, and of the participants who suggested game improvements, many involved ways that these alternate interactions could be expanded in future versions of the game. Some of these suggestions included the UFOs getting increasingly hard to kill, more UFOs coming at the player at once, or enemies that were aliens. The addition of these features in future versions of the game would add some variety to game play, and may increase the replayability of the game. Though Astrojumper can be set to last an arbitrary amount of time, for this study, we knew we would be evaluating player interaction over a relatively short game play interval. For this reason, additional ways to keep players motivated to play over an extended period of time, such as alternate levels or some of the ideas the participants suggested, were not implemented in this version of Astrojumper. However, in future versions of this game that will be evaluated over extended periods of time, features that will keep players coming back will be included.

Participants perceived that they had experienced a workout, and these subjective reports were corroborated by the physiological measure of heart rate. However, since we included a cooldown phase at the end of the game session, by the time we measured participants' exerted heart rates, they had time to drop from the peak levels reached during exercise. Despite that fact, we observed an increase of 29.6 beats per minute (38%) on average even after the cooldown phase. We were encouraged by these results, and by our qualitative observations that participants often did, quite literally, work up a sweat. The talk test is a common self-test used to measure whether a person is exercising in his or her target heart rate zone; if you find it hard to talk, you are in the zone. We observed that most players were unable to talk just after playing Astrojumper. In future studies we will ask participants to report on this.

From our observations, the dynamic difficulty adjustment worked well as a game mechanic, since participants made no negative comments on our feedback questions about the difficulty. We did not observe any cases where participants appeared either bored or frustrated. We are interested in further exploring this technique, and possibly introducing more sophisticated approaches, such as scaling the difficulty based on direct measurements of heart rate (Stach, Graham, Yim, & Rhodes, 2009).

From the qualitative comments, it is clear that stereoscopy was a motivating factor for participants, as some specifically mentioned stereoscopy (which many referred to simply as "3D") as one of the most exciting parts of the game. Almost all participants expressed excitement when they first put on the stereoscopic glasses and saw the game environment, such as laughing or exclaiming sentiments such as "it's like the planet is right in front of me!" Further analysis needs to be done to see how much of the participants' enjoyment of the game can be attributed to the stereoscopic factor. While many participants expressed the idea that they felt immersed in the game, it was not clear whether this was due to the stereoscopic 3D or the three-screened CAVE environment. Future studies are planned to isolate these factors.

5 Conclusion and Future Work

In this paper, we presented Astrojumper, a virtual reality exergame designed to engage the user in immersive, full-body exercise. The results of our user study were promising, and demonstrate that stereoscopic virtual reality exergames have strong potential to motivate physical activity in both children and adults. In future studies, we plan to directly compare the benefits of virtual reality with less immersive exergame platforms that do not employ stereoscopy, such as the Wii Fit. Additionally, it may be possible to increase accessibility for a wider audience by using commodity wireless motion tracking instead of electromagnetic trackers, and by deploying Astrojumper on a less expensive portable stereoscopic projector or 3D television. Finally, we are also very interested in studying different user populations to further investigate design issues for exergaming.

We acknowledge that since virtual reality technology is not yet widely accessible, some of our participants' positive reactions may have been due to a novelty factor.

In the future, we plan to perform longitudinal studies to examine the long-term effectiveness and motivation potential of Astrojumper. To maintain interest after repeated exposure, we intend to implement additional levels and themes, boss fights, and alternate interaction possibilities, such as new gestures and game mechanics.

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