Novel Motor Training Environments Improves the Sense of Agency and Movement Coordination

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1.0 Abstract:

Conventional rehabilitation methods for motor disabilities predominantly focus on the recovery of motor functionality through unimodal and monotonous training regimens; by neglecting the concurrent treatment of the cognitive and physical aspects of neuromuscular trauma, rehabilitation only leads to the partial recovery of motor function. To optimize rehabilitation efficacy, training must adaptable, accessible, and engaging while developing the sense of agency — a user's sense of volition over an action — and providing multimodal sensory feedback. Therefore, this study developed and tested the efficacy of two novel gamified motor training environments through the platform Unity® supplemented with assets created in various art, 3D modeling, coding, and audio programs. The tasks trained the sense of agency through the use of implicit and explicit measurements; investigated the effect of varying sensory outcomes on intentional binding efficacy; and observed perceptions of agency to compare it to performance. Pilot data (n=6) demonstrated that continuous use of the novel tasks increased the instances of high agency, task completion speed, and improved movement coordination. It was observed that retrospective feelings of agency did not correlate with performance, confirming that an imposed false sense of agency through tracking delay negatively affects perception; however, continually training with the imposed delay led to an improvement in performance. Furthermore, the presence of varying control methods and sensory outcomes did not significantly affect agency instances; rather, affected task performance. The training environments developed through this study are capable of being used in rehabilitation facilities focused on the recovery of motor functionality following neuromuscular trauma.

2.0 Introduction:

In the United States, 1 in 6 adults has a disability that limits motor function [1]; motor disabilities are often caused by traumatic brain injury, spinal cord injury, or cerebrovascular accident [2, 3, 4]. Motor disability induced by neuromuscular trauma requires targeted rehabilitation to restore the damaged motor functionality [3]. Conventional rehabilitation methods focus on training the physical aspects of rehabilitation through the implementation of repeatable and adaptable exercises critical for improving complex motor learning [2, 5, 6]. However, the sole focus on physical recovery neglects the cognitive aspect of motor rehabilitation [3]. This tends to negatively affect the patient by making training monotonous and stagnant, thus, leading to only the partial recovery of motor function [5, 7]. To optimize motor rehabilitation, various factors of an individual's condition must be considered to create a personalized and adaptable rehabilitation experience [6].

The efficacy of rehabilitation depends on the adaptability, accessibility, and user-engagement in the training regimens [7, 8]. Although previous studies have shown that repeatable exercises are essential in a patient's motor recovery, the method in which they are applied can determine the efficacy of rehabilitation. Traditionally, rehabilitation exercises focus on providing unimodal feedback to the patient during training, however, studies have shown that this approach does not effectively restore physical and cognitive control over motor functions [5, 7]. The application of multimodal feedback, the presence of multiple sensory feedback types, in rehabilitation promotes complex motor learning by increasing user-immersion in training exercises [5, 6, 9]. Recently, the use of virtual environments for rehabilitation has come to prevalence due to its ability to simulate real world actions and provide modifiable and personalized training exercises to improve on adaptability, accessibility and immersion. Virtual training improves cognitive engagement and complex motor learning by presenting vivid sensory feedback, providing concurrent reinforcement training, and increasing motivation through the use of gamified tasks [3, 7, 8, 9, 10]. The concurrent training of physicality and cognition in virtual motor rehabilitation optimizes the efficacy of these regimens by improving the connection between an individual, an action, and rehabilitation method [5, 6]. Therefore, this study designed gamified rehabilitation tasks through a virtual format that implements cognitive training to improve the connection between the user, the action, and the developed rehabilitation program.

The connection between an individual and ownership over an action is known as the *sense of agency*; this connection promotes the feeling of volition over one's actions and the knowledge of the suspected outcomes [11, 12, 13]. The sense of agency is crucial in the connection between physical and neurological processes [6, 11]. Motor disabilities cause agency to be lost or limited, this loss of agency leads to further degradation of limb function [14].

The sense of agency can be measured through two methods: implicit, measurement through performance, and explicit, measurement through direct statement [11]. This study implemented the use of intentional binding to measure user-agency in a series of motor training tasks. Intentional binding is an implicit method of agency measurement that was introduced by Haggard et al. in 2002 (**Figure 1**). Haggard 2002 found that when a voluntary action occurs, the perceived time interval between the action and the outcome was slightly shorter than in reality [15, 16]. These perceptions of time intervals signify a sense of agency between the user and the action. In motor rehabilitation, the training of the sense of agency with regimens that build enthusiasm around training improves the engagement of the user which promotes complex motor learning [6, 7, 8].

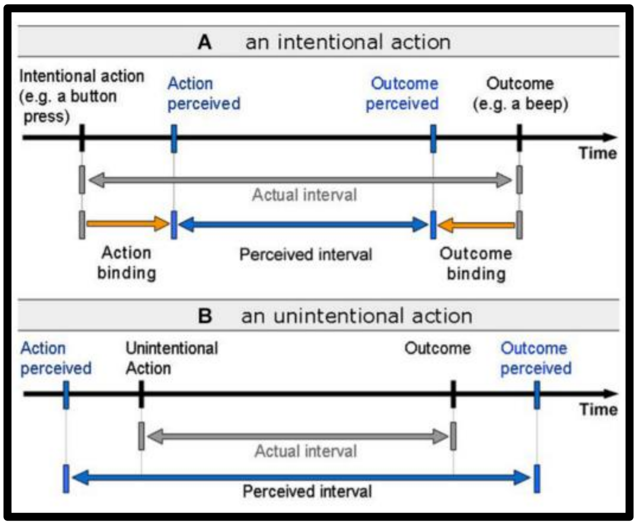


Figure 1 [9]:
A) *When an intentional action occurs, the perceived time interval between the action and the outcome is shorter than in reality.*
B) *When an unintentional action occurs, the perceived time interval between the action and the outcome is greater than in reality*

The efficacy of rehabilitation training relies heavily on the effort of the user. Training has to be designed to be engaging and motivating to promote continuous training and aid the recovery process to restore the lost motor functionality [7, 8]. Monotonous and repetitive training decreases motivation, which, in turn, decreases the attention given to training [7]. User immersion can be improved through the implementation of training regimens that support a balance between challenge and engagement [9]. Gamified training environments provide this balance as the user experiences the sensations of competition, feedback, and progressive difficulty. Rehabilitation methods can work to regulate this balance by providing reinforcement on user performance.

Numerous studies have shown that the application of either positive and negative feedback, motivation, or punishment enhances complex motor learning and neuroplasticity, which improves the efficacy of training regimens [17, 18, 19, 20].

Our study developed two engaging, accessible, and adaptable virtual training environments that focused on:

1) Improving user-agency and movement coordination while investigating the effects of positive and negative motivation on training.
2) Determining whether varying sensory outcomes influence agency through intentional binding.
3) Observing personal feelings of agency and comparing them to performance.

It was hypothesized that the developed methods were efficient in improving movement coordination and the sense of agency. It was also hypothesized that the variation of sensory feedback intentional binding affects user-agency within the environment.

3.0 Methodology:

3.1 Development of the Training Environments:

3.1.1 ***Development in Unity®:***

All of the novel training environments were developed using Unity 2019 and 2020®. Unity's 3D templates were used to develop the intentional binding training environment (**Appendix A, Appendix B**). Unity 2D was used to develop the movement control task as well as the feedback task. All functionality and logic for the environments were coded in C# through Visual Studio 2019® (**Figure 2B, Appendix C**).

3.1.2 Asset Design:

Various assets (3D models, sprites, images, and audio files) were specifically designed for use in the training environments. The 3D modeling software, Blender® (**Figure 2A**), was used to design the 3D hand for the intentional binding tasks. The graphic design tool, Gravit®, was used to create 2D assets for the movement coordination task as well as images to explain the controls of the game in the "How to Play" section. Audio files for the auditory feedback variation of the intentional binding task were sourced from royalty free websites. To further develop the game aspect of the feedback environment, an open-source version of Aseprite®, Libresprite® (**Figure 2C**), was used to design 2D pixel art. Narration and commentary were recorded and edited in FL Studio 20® (**Figure 2D**). Ambient noise was sourced from the royalty free website, FreeSound.

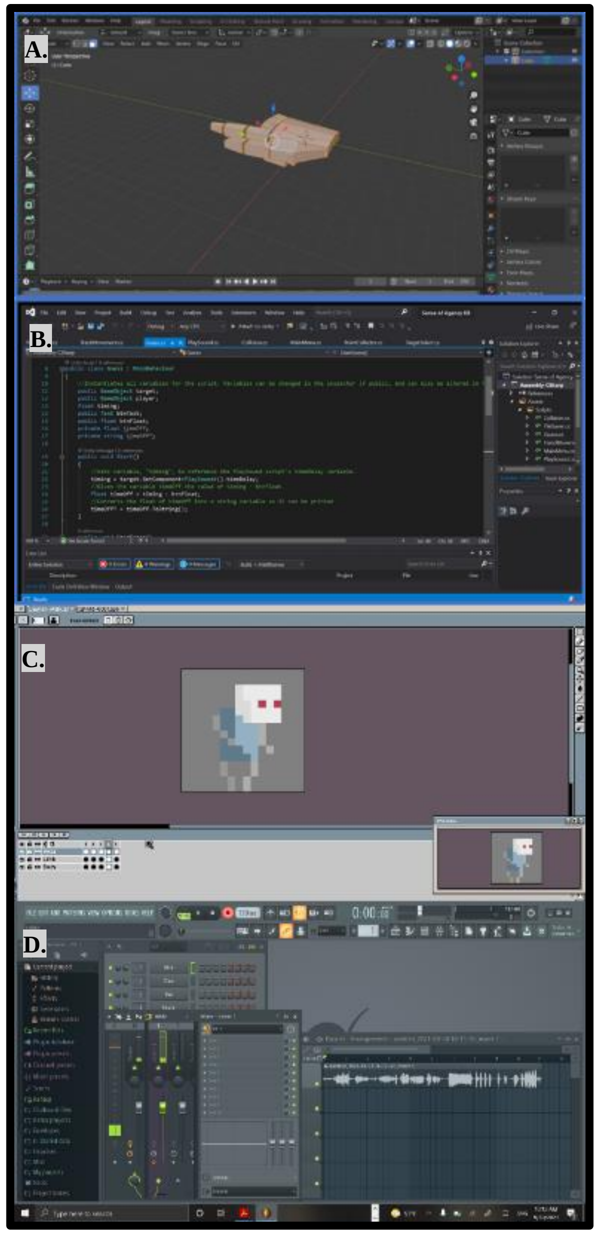


Figure 2A, 2B, 2C, 2D: *The tools used for the development of the training environment.* ***2A:*** *screenshot of 3D hand modeling in Blender®* ***2B:*** *Screenshot of movement code in Visual Studio 2019®* ***2C:*** *Screenshot of sprite creation using Libresprite®* ***2D:*** *Screenshot of FL Studio 20® program for vocal recording.*

3.2 Environment 1 - Sense of Agency Training:

A focus of this study was to make motor training more engaging for the user in order to increase enthusiasm and improve complex motor learning. The functionality and design of the training environments were made to replicate a game. The movement coordination task was designed to replicate a dodge-the-blocks game, and the intentional binding tasks were designed to replicate a touch-the-target game. The development of gamified training tasks increases user engagement; this allows for improvement in enthusiasm toward training.

3.2.1 Intentional Binding Tasks:

The intentional binding tasks were designed to train and measure the sense of agency in a user. The type of sensory feedback varied in these tasks between auditory and visual. In these tasks, a dynamic target moved across two points on the x-axis (**Figure 3**). The functional goals were:

1) Contact the moving target by controlling the hand.
2) Make a prediction on the time interval in which a sensory outcome occurred.

The factors observed in this task included the effect of sensory feedback on instances of agency; when a user contacted the target, a sensory consequence would occur dependent on the task variation active; and the effect of method of control on performance as the tasks supported the use of keyboard-and-mouse and keyboard-and-trackpad. Performance in these tasks was defined as the average time to complete a trial (in seconds) and the instances of high agency. Participants performed two sets of 10 trials per task variation. Participation in the intentional binding tasks required approximately 7 minutes. Participants were given five practice trails in between every task variation for acclimation to the tasks.

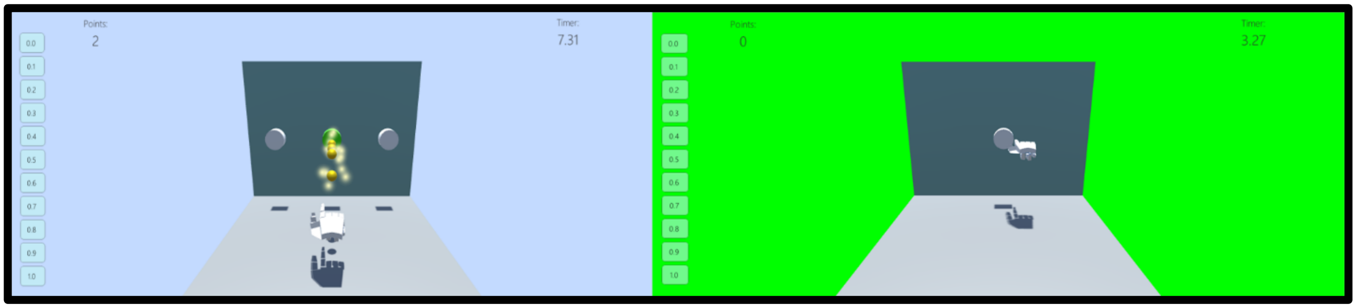


Figure 3: *Intentional Binding Training Tasks. The player (hand) is meant to contact the target (circle) and estimate the time interval at which a sensory outcome occurred. The image on the left is a screenshot if the auditory variant, the image on the right is a screenshot of the visual variant.*

3.2.2 Point System for Intentional Binding Tasks:

This study utilized the Haggard et al. (2002) intentional binding paradigm to measure agency in the tasks. In these tasks, when the target was contacted by the player, a sensory outcome occurred between 0.1 – 1.0 seconds. Using this principle, a novel point system was developed to quantify agency. If the user correctly guessed the exact delay, one point was rewarded which solely served as reward feedback to encourage the user and did not signify anything in data analysis. If the user under evaluated the delay by 0.1 seconds, 2 points were rewarded which served as an indicator for instances of high agency over the environment. The accumulation of two agency points signified a higher sense of agency, one point or zero points did not.

3.2.3 Movement Coordination Task:

The movement coordination task aimed to train the reflex timing and movement accuracy through a dodge-the-blocks game (**Figure 4**). This task introduced a discrete decay in mouse sensitivity to test a user's explicit feelings of agency. Sense of agency training was implemented in this task explicitly in a form given after testing which questioned the user on: engagement, feelings of control over the environment, and opinions on the developed training environment. Training was conducted using a mouse or trackpad where the user-controlled a ball and had to dodge a row of blocks that fell at a rate of one row per second. The user completed 10 trials of this task; after each trial, the sensitivity in the mouse was reduced by 10 (the base was 80 – where the position of the ball fully matched the position of the cursor). Additionally, a steady increase of 0.05 seconds-per-row in the rate at which the row of blocks fell was introduced to make the game more challenging as participants progressed. The leading performance variable tracked in this task was the total time (in seconds) evading the blocks. Through relating this performance with the reported feelings of agency, we could observe whether a user's feelings of agency corresponded with performance.

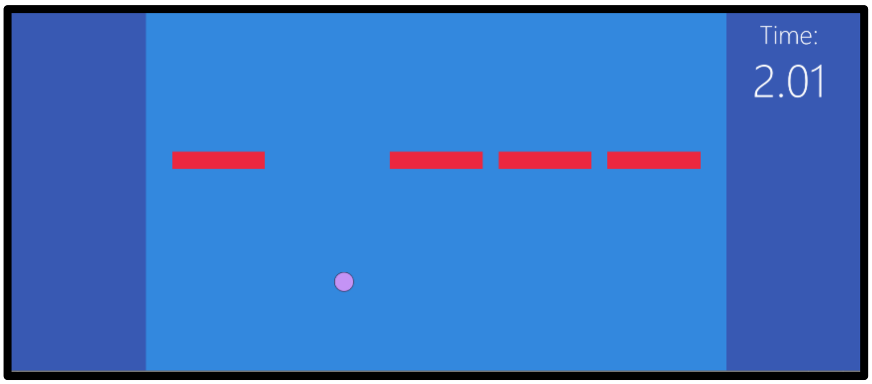


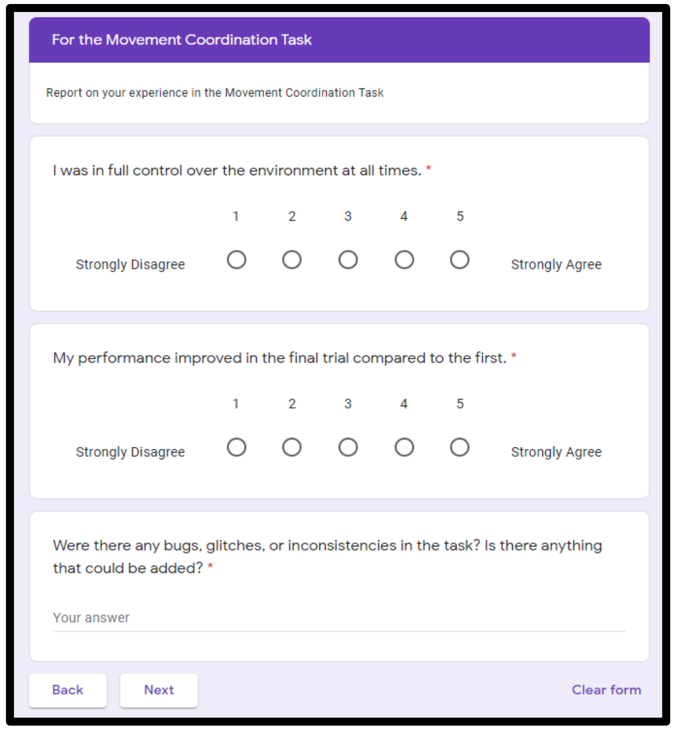
Figure 4: *Movement Coordination Training Task. This task was designed to resemble a "dodge the blocks" type of game. The player (pink circle) is tasked with moving through the empty spaces as the obstacles (red bars) fall towards the bottom of the screen.*

3.2.4 Participant Recruitment:

This study used six able-bodied adolescents to test the efficacy of the novel training environments (n = 6). Participants were all from the same high school and performed training unsupervised at home or supervised in the school's library. The game file was sent through email to an unsupervised participant (n = 1); supervised participants (n = 5) performed training under the observation of the student researcher through a common desktop computer that the game file was downloaded onto, the method of control remained as keyboard-and-mouse for all participants. The appropriate consent and post-testing forms were sent via email to all participants.

3.2.5 Post-Testing:

A short questionnaire was developed in Google Forms® for participants to allow them to report on the factors being measured explicitly in this study (**Figure 5**). The form contained questions regarding participants' experience during testing, including rating the attractiveness and the difficulty of the tasks. These values were measured on a Likert Scale ranging from 1 (strongly disagree) to 5 (strongly agree). Explicit measurement of agency was included in this form where participants answered regarding feelings of control over the environment and their retrospective performance in the training tasks. The values collected through this form serve as a comparison with training task performance to evaluate user perception of training performance. Data was transferred from Google Sheets to Microsoft Excel for further analysis.


For the Movement Coordination Task

Report on your experience in the Movement Coordination Task

I was in full control over the environment at all times. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

My performance improved in the final trial compared to the first. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

Were there any bugs, glitches, or inconsistencies in the task? Is there anything that could be added? *

Your answer

Back Next Clear form

Figure 5: *Screenshot of the form developed for participant feedback on explicit agency, perceived performance, and supplementary factors related to the user-experience in the gamified environment.*

3.2.6 Data Organization:

Following a completed trial, .csv files were printed into the game folder. The .csv files contained performance variables on trial number, points accumulated, time to complete trial (seconds), delay, and delay guess. The participants sent the printed files via email which were compiled in Microsoft Excel 2020® by the student researcher. The task data was organized by participant, test number, and task type. This data was later compiled, organized, and graphed in GraphPad Prism 9®.

4.0 Results:

4.1 Continuous Training Improves Performance:

The developed training tasks aimed to increase the number of instances where the user experienced high agency with the environment. In the first test of the auditory variation from the intentional binding task in the sense of agency environment, the mean time to complete a trial was 3.18 seconds and the mean agency point value was 0.36 (**Figure 6A**); in the first test of the visual variation the mean time to complete a trial was 2.51 seconds and the mean agency point value was 0.44. In the second test of the auditory variation the mean time to complete the trial was 2.04 seconds and the mean agency point value was 0.88 (**Figure 6B**); in the second test of the visual variation, the mean time to complete a trial was 1.90 seconds and the mean agency point value was 0.67. In all task variations observed, the instances of high sense of agency scores, and task completion speed increased by the second test.

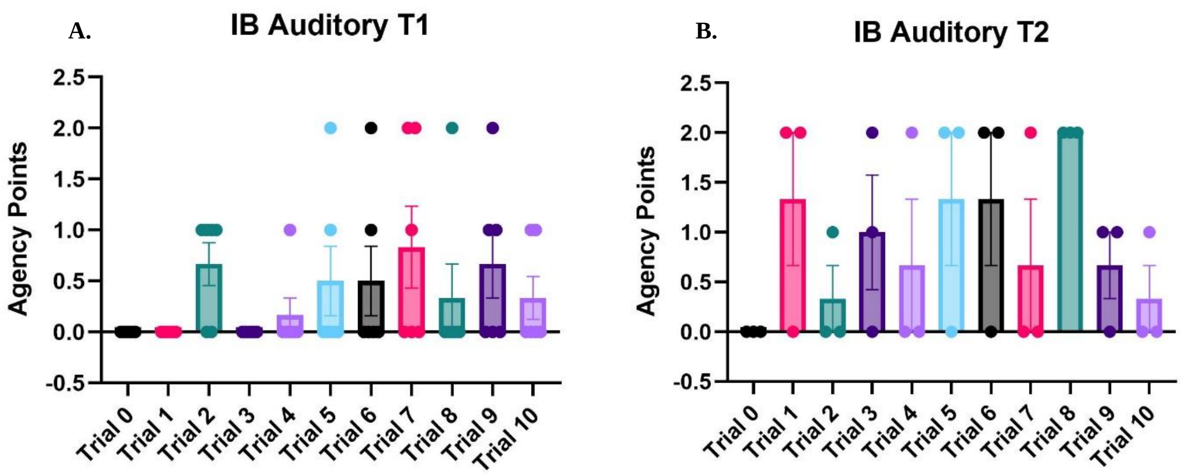


Figure 6A, 6B:

The plotted dots represent the individual (n = 6) accumulated agency points by participant and trial number. The bars represent the mean agency points by trial

A) *The performance results for the first test of the Auditory Task. (Six high agency instances).*

B) *The performance results for the second test Auditory Task. (12 high agency instances).*

4.2 Varying Sensory Outcomes and their Effect on Agency:

Variations of sensory feedback, following contact with the target in the task, was a factor we aimed to evaluate in this study in effort to observe the effect it may have on agency through intentional binding. It was found that in the first trials, the instances where higher agency was recorded were greater with the visual feedback (eight instances of high agency) than the auditory feedback (six instances of high agency) (**Figure 7A**). However, in the second trials, the instances where higher agency was recorded were greater in the auditory variant (12 instances of high agency) than the visual variant (eight instances of high agency) (**Figure 7B**).

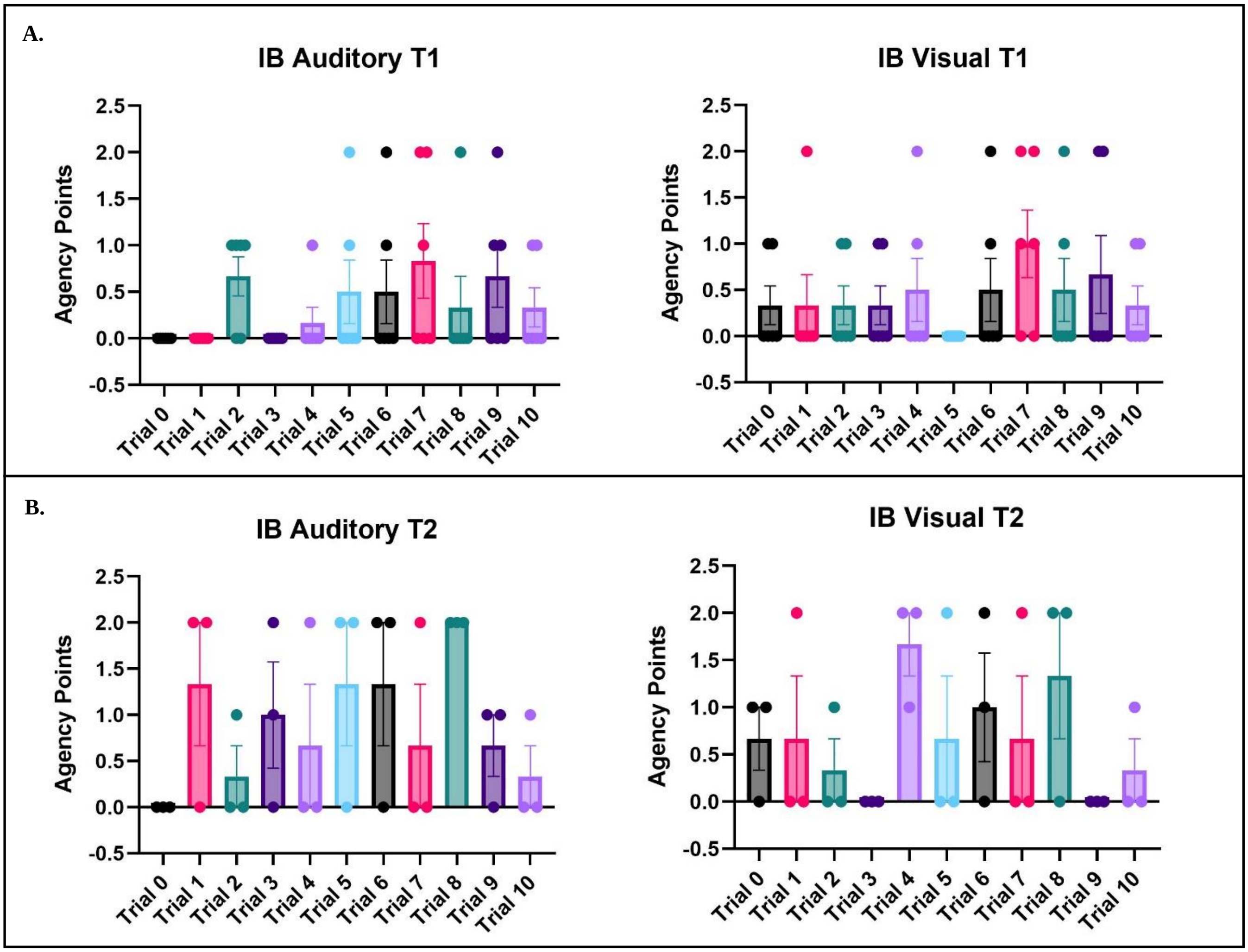


Figure 7A, 7B:

The plotted dots represent the accumulated agency points per participant and trial number. The bars represent the mean agency points by trial.

A) *A comparison between the accumulated agency points in the first tests of the Auditory Task and the Visual Task per participant. In Auditory Task, six instances of high agency were recorded; in the Visual Task, eight instances of high agency were recorded.*

B) *A comparison between the accumulated agency points in the second tests in the Auditory Task, 12 instances of high agency and the Visual Task, eight instances of high agency were recorded.*

4.3 Movement Control Task Improves Movement Coordination but Impedes Retrospective Performance:

The movement control task designed to allow for agency to be measured explicitly. The purpose of this task was to determine if perceived agency coordinated with performance. The leading performance variable tracked was the time to complete a trial where greater values indicated better performance (participants were more successful in evading the falling blocks). Through the data observed, user-performance in the task had a near-direct relationship with the tracking delay introduced throughout the trials (**Figure 8**). Comparing tracked performance with self-reported retrospective performance, participants represented a good understanding as the mean time to complete all trials in the first test was 12.04 seconds, whereas the second test yielded a mean time of 15.1 seconds. In the post-testing questionnaire, participants reported either a 4 or a 5 (agree - strongly agree) under "My performance improved in the final trial compared to the first". However, reports of control over the environment did not correlate with the tracked performance as participants responded with either a 4 or 5 under "I was in full control of the environment at all times"; throughout the task, a tracking delay was introduced which decreased the amount of control participants had over the environment. This shows that participants had a good sense of retrospective performance but a false sense of agency during testing.

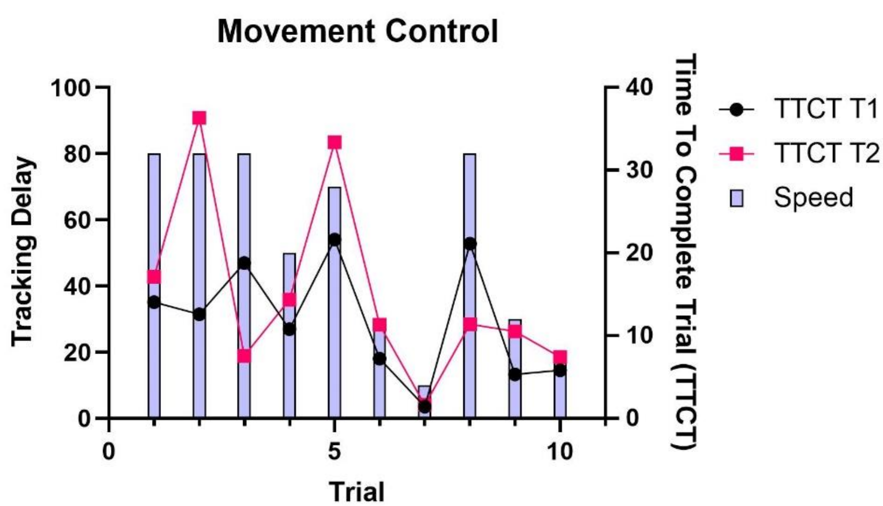


Figure 8: *Mean performance in both Movement Control Tests by trial number. Bars represent the mouse tracking delay value (80 – full tracking). The first test performed slightly worse ($\bar{x} = 12.04\ seconds$) than the second test of the same environment ($\bar{x} = 15.1\ seconds$). All values demonstrated represent the mean time across an $n = 6$ population.*

<u>5.0</u> <u>Discussion:</u>

This study developed two novel motor training environments for the rehabilitation of motor disabilities caused by neuromuscular trauma. Thereafter, environments were tested using a cohort of volunteers whose performance in the tasks and feedback on a short form provided insight on engagement and functionality of the gamified tasks. Pilot data shows that continuous training improves user performance in the Sense of Agency training environment. We saw that repeated use of the intentional binding tasks resulted in more frequent the instances of high agency. When observing the effect of varying sensory stimuli (auditory versus visual) on instances of agency, results show that agency does not seem to depend heavily on differences in stimuli. We observed the effect of an imposed false sense of agency on performance in the Movement Control environment, this shows that user performance directly depended on the change in mouse tracking delay. Explicit reports of retrospective agency show that participants did not recognize the imposed tracking delay as impeding on their agency over the environment. The pilot data confirms that the developed methods are efficient in improving performance and increasing instances of high agency through continuous use.

Virtual environments, such as those designed herein can optimize rehabilitation by enhancing sensory feedback in an engaging environment [3, 7, 8, 9, 10]. The developed methods aimed to be efficient by implementing sense of agency training and multi modal sensory feedback through gamified virtual training. Our results show that the continued use of the Sense of Agency environment improves performance, this suggests that over time, the cognitive processes involved in agency will develop with repeated training. This study hypothesized that the variation in sensory outcomes during intentional binding would affect the number of high-agency instances recorded. Pilot data refuted this hypothesis by showing that variations in feedback did not have a significant effect on agency instances. This finding is supported by David et al. (2016), where they found that agency was more dependent on variations in outcome actions rather than sensory modalities [21]. The final variable this study observed, was participants' retrospective perception of performance and agency compared to their actual performance. It was found that participants correctly perceived their improvement in the tasks, however they did not correctly perceive their agency scores with the imposed delay. This suggests that perceptions of performance and agency are separate.

Training was limited to use on a desktop or laptop with a keyboard-and-mouse or a keyboard-and-trackpad control input. The training environment was designed to offer flexibility in the method of control the user employs so that the training environment can be used in a clinical setting where it can easily be adapted for the individual needs of a patient. can be modified to function on motion capture, virtual reality, or augmented reality set-ups.

The developed methods were designed to rehabilitate motor functionality lost as a result of neuromuscular trauma; however, this study was only able to perform pilot testing on able-bodied participants. The nature of the training environments allows them to be easily adapted and applied to multiple situations, including rehabilitation facilities for traumatic brain injury, spinal cord injury, or cerebrovascular accident. In the future, the developed methods should be tested on a clinical population with the use of a virtual reality, augmented reality, or motion capture set-up. Haptic feedback should also be added to the sensory feedback variations to fully investigate the varied sensory modality hypothesis.

An untested secondary task — The Feedback Task — was additionally developed for this study; this task focused on providing disproportionate positive and negative feedback to participants and observing the effect on motivation and performance.

5.1 Environment 2 - Feedback Task:

The feedback task was focused on observing the effects of positive and negative motivation on performance. It has been shown that positive feedback improves intrinsic motivation through providing rewards that stimulates better behavior. Negative feedback is widely believed to have the opposite effect; however, it has been observed to sometimes stimulate better behavior and improving performance [19]. This task was designed in a gamified environment as a 2D Platformer in order to immerse the

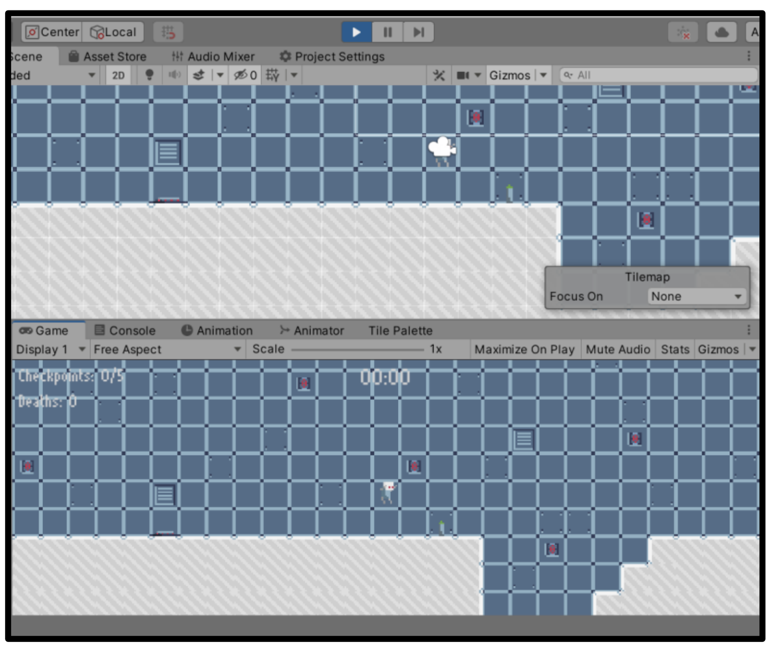


Figure 9: *Feedback Task development using Unity®. Uppermost image shows the Unity developer view, Lowermost image shows the game view (what the participant sees).*

user in training (**Figure 9**). The performance variables tracked in this environment were: time to complete level, number of deaths, and the amount of collected optional sprites. The task supports three variations of the game where the application of disproportionate positive and negative feedback varies between groups. In the positive feedback group, training levels were narrated by a “nice” commentator that congratulates the players regardless of their performance. The negative feedback group focused on training with a “mean” commentator that provides negative feedback regardless of performance. The control group featured levels with no commentary, simply instructions on each level. In order to efficiently observe the effect on performance, the negative feedback commentator provided snarky comments on how to improve performance as to not demotivate the user but instill a fear of failure. Variations in audio tones correlate with each environment variation where the positive group contained higher toned pitches associated with positive feedback, and the negative group contained lower toned pitches associated with negative feedback.

6.0 Conclusion:

This study developed three novel motor training tasks for the rehabilitation of motor functionality following neuromuscular trauma. Pilot data confirmed the efficacy and functionality of the developed methods by showing an improvement in movement coordination and an increase in the instances of high agency. The outlook for this research is the implementation of these tasks or variations of these tasks to be used in motor rehabilitation settings. This method of training offers the adaptability and variety required in efficient motor rehabilitation while implementing multimodal feedback and intentional binding to improve the sense of agency and movement coordination.

7.0 Acknowledgements:

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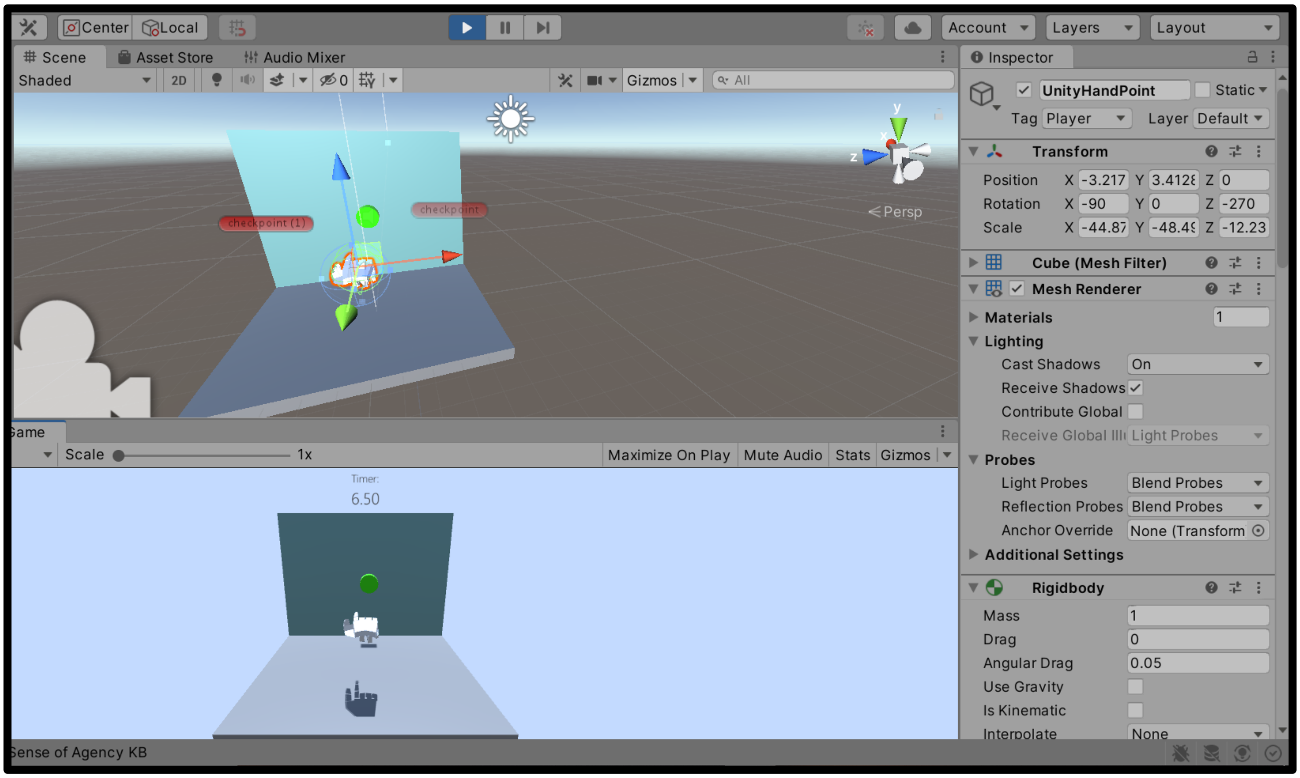
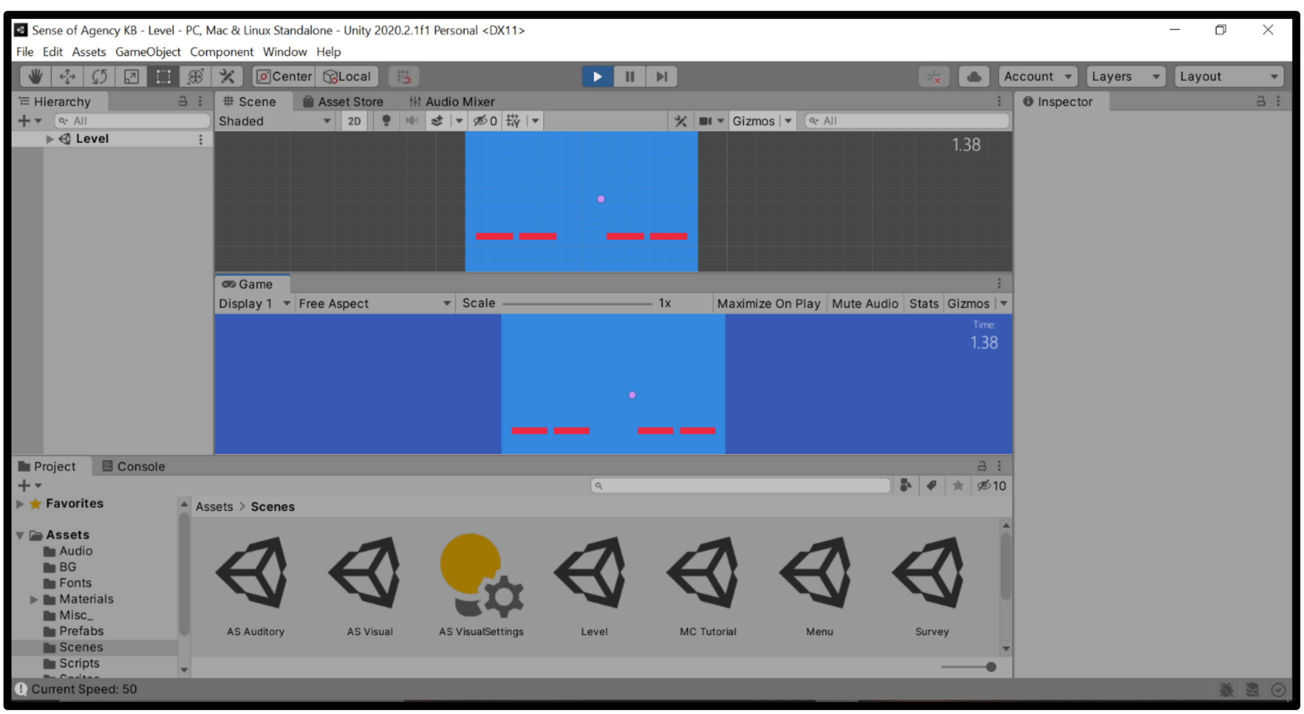
9.0 Appendix:

9.1 Appendix A:



9.2 Appendix B:



9.3 Appendix C: