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Increasing Voluntary Myoelectric Training Time Through Game Design

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***Abstract*—In virtual prosthetic training research, serious games have been investigated for over 30 years. However, few game design elements are used and assessed for their effect on the voluntary adherence and repetition of the performed task. We compared two game-based versions of an established myoelectric-controlled virtual prosthetic training task with an interface without game elements of the same task [for video, see (Garske, 2022)]. Twelve limb-intact participants were sorted into three groups of comparable ability and asked to perform the task as long as they were motivated. Following the task, they completed a questionnaire regarding their motivation and engagement in the task. The investigation established that participants in the game-based groups performed the task significantly longer when more game design elements were implemented in the task (medians of 6 vs. 9.5 vs. 14 blocks for groups with increasing number of different game design elements). The participants in the game-based versions were also more likely to end the task out of fatigue than for reasons of boredom or frustration, which was verified by a fatigue analysis of the myoelectric signal. We demonstrated that the utilization of game design methodically in virtual myoelectric training tasks can support adherence and duration of a virtual training, in the short-term. Whether such short-term enhanced engagement would lead to long-term adherence remains an open question.**

***Index Terms*—Motivation, engagement, prosthetics, serious games.**

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Newcastle University Ethics Committee.

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I. Introduction

ENGAGEMENT is a key factor in adherence to medical exercise regimen. However, adherence of patients to interventions remains a challenge in rehabilitative medicine [1]. Rehabilitation in general is a process that needs time and consistency to reach its full potential. Serious games can enhance motivation and facilitate adherence to therapy [2], [3], [4]. For example, research on the utilization of serious games in stroke rehabilitation has shown significant benefits to the users including an increase in the number of performed repetitions [5].

Likewise, the use of serious games for training upper-limb prosthesis use has been considered for more than 30 years [6]. However, existing approaches vary significantly and published literature are not founded on established game design principles explicitly [7]. The prosthetic research that does intentionally incorporate motivational principles in their game design [6], [8], [9] predominately falls back onto the works of Lepper and Malone [10], [11] and Flatla *et al.* [12], who consolidated Malone's motivational principles with other sources into game design principles.

Malone *et al.* [11] distinguished individual and interpersonal motivations with the former comprising challenge, curiosity, control and fantasy. Specifically,

- *challenge* dictates that the difficulty should be appropriate for the player to avoid frustration and/or boredom;
- *curiosity* can be evoked by sensory stimuli, e.g. sounds, and cognitive stimuli, e.g. riddles;
- *control* can incorporate a long list of factors, e.g. the responsiveness of the environment to the player's choices and a feeling power and agency; and
- *fantasy* includes the representation of the task at hand and serves to make it more interesting and fun in an aesthetic and emotional capacity.

Malone *et al.* [11] further described interpersonal motivations as competition, cooperation and recognition. These factors depend on other people and can lead to strong intrinsic and extrinsic motivational effects.

Flatla *et al.* [12] also focused on four key design principles: challenge, theme, reward and progress, with challenge being an overarching principle, in harmony with the literature [11], [13], [14]. Rewards reinforce behavioural patterns [12]. They can be used as a tool to keep the player engaged short-term and long-term, or as feedback [1], [15]. Positive feedback is more effective for motivation, motor learning as well as the feeling of competence [15].

A more sensory oriented principle is called theme [12] which incorporates the motivational principle of fantasy [11]. This principle does not necessarily affect any game mechanics, but is incorporated via the aesthetic representation and theme of the game and is therefore present in most games. It can provide a more engaging experience for that player than the base task by providing an interesting surrounding and also enhance the feeling of immersion to the game's world. This can take the player's focus away from their own body and onto the task, which can be beneficial for motor learning [16]. Immersion furthermore feeds into the state of "Flow", in which the attention is focused on the task and the user has an enjoyable experience [17].

This article is the first to compare the use of game design principles applied to one task in the context of myoelectric control as well as to relate these to survey results and physiological measures. Specifically, we utilise the game design principles of challenge, sensory curiosity, control, and fantasy while focusing on retaining the task and therefore the mechanism with which the benefit of training is delivered [18]. We hypothesized that adding game design elements to a given myoelectric task can increase the user engagement and motivate them to voluntarily perform this task for longer.

II. Methods

A. Participants

Twelve adult limb-intact people took part in this experiment. Previous research shows that there is no significant difference in the gaming behaviour of people with or without disabilities [19] and therefore the motivational effect of game elements is expected to be comparable for both population groups. All participants were students or employees of Newcastle University and the University of Edinburgh. Five participants had previous experience of myoelectric control. Approval was granted by the local ethics committee at Newcastle University (ref. 15266/2018). All participants gave informed written consent.

B. Setup

A Shimmer EMG unit (Shimmer Research Ltd., Ireland) was used to record the electromyography (EMG) signals from the dominant forearm targeting flexor carpi radialis (FCR) and extensor carpai ulnaris (ECU). We used disposable wet snap electrodes (otometrics, Natus Nicolet, UK). Furthermore, a Shimmer GSR+ unit was attached to the index and middle fingers of the non-dominant hand by reusable snap electrodes embedded in a hook-and-loop fastener band. This was used to record the galvanic skin response (GSR) during the experiment as a measurement for the emotional arousal to indicate the level of engagement of the participant [20], [21].

Both Shimmer units were linked to the recording setup via Bluetooth. The recording machine was an Alienware M15 Ryzen™ edition R5 gaming laptop (AMD Ryzen™ 7 5800H, NVIDIA Geforce RTX 3070, 16GB DDR4). The EMG signals were sampled at 1024 Hz and band-pass filtered (30-500 Hz) via the Shimmer API. We calculated the game control signals by smoothing the absolute value of the EMG signal over a 750ms window, in line with Dyson *et al.* [22] and Pistohl *et al.* [23] for responsive movement and a sufficiently smooth output signal. The screen was updated at 50Hz.

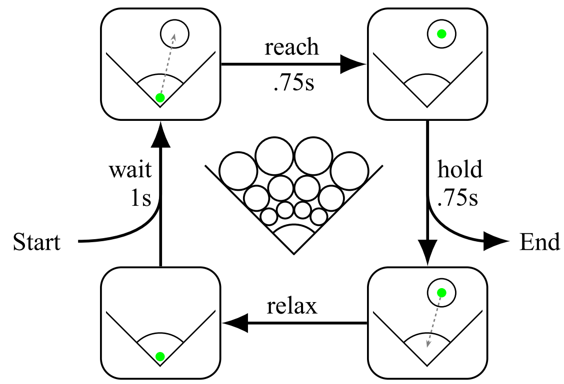

Fig. 1. The base task loop: the player stayed in the rest zone for 1s, had 750ms to reach the target, 750ms to stay in the target and then relaxed to return to the rest zone. A depiction of the whole task space with all targets is shown in the center.

C. Task

The game was created by the lead author using Unity Game Engine (Unity Technologies, Inc), as detailed in Section II-D. All utilized virtual assets were freely available in the Unity Asset Store. The participant controlled a cursor (or avatar) in a V-shaped task using the two input EMG channels. The input is mapped to the x- and y-coordinates of a cursor in a task space that is equivalent to the first quadrant of a Cartesian coordinate system rotated counterclockwise by 45°. This task replicates abstract decoding, a myoelectric control scheme which has been tested in both in limb-intact and limb-different participants [22], [24]. Figure 1 illustrates the task space as well as the task loop.

The participant was tasked to move the cursor from the resting position and reach a circular target within 750ms (the reach phase) before the scoring starts. Then they have to remain in the target for the remaining 750ms of the duration of their appearance (the hold phase). Following each trial, participants received a score between 0% to 100%, which reflected how long they kept the cursor within or touching the target area during the hold phase. Each block contained 48 trials. The task space comprised twelve targets as depicted in the center of Figure 1. Each target appeared 4 times per block in a pseudo-randomized order.

D. Software

A prototype was developed in the Unity Game Engine. It connected to the Shimmer devices, enabled signal conditioning and incorporated three implementations of the myoelectric task. The interfaces contained an increasing amount of game design elements from the basic over the static to the dynamic interface, as shown in Figure 2. Each interface contains the elements implemented in the previous one and has some elements added to it. A video demonstration is available online [25] and a detailed description of each interface follows:

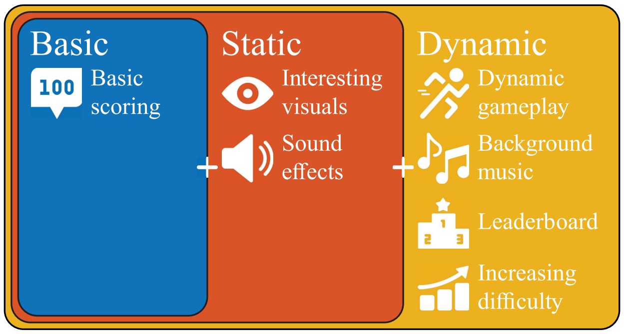

Fig. 2. Increasing number of game design elements included in the different interfaces.

1) Basic Interface: This interface presented the task in its most basic form. On a neutral background (black), the small quadrant representing the rest zone was always visible and the circular targets appear as they are presented. The start and the end of the each trial was cued with a beep. At the end of each block, the average hold score for the block was displayed as a percentage. No specific game design principles were incorporated.

2) Static Interface: We enhanced the visuals in the static interface to incorporate the fantasy and curiosity game design principles, as explained in the introduction. However, it retains the perceived static nature of the basic interface. Specifically, the environment was a rocky caldera and the user controlled a flying dragon. Targets were a circular array of gemstones. The player was tasked to collect gemstones when flying over them. These gems reappeared almost instantly during the reach and hold phases, so that the player had an incentive to stay within the target during the hold phase. The collection of a gem triggered a popping sound and added points to the total score of the current block on the bottom of the screen, which acted as a simple reward and feedback system. The scoring was changed from an average percentage score to a point score depending on the number of collected gems.

3) Dynamic Interface: We aimed for a more dynamic environment in this interface by adding two game design principles: challenge and competition. The participant's avatar was the same dragon as in the static interface, but it was designed as an endless runner, i.e. consistently flying through the valley. The interface also included energetic music.

The targets were presented as a row of gems that appeared at the far end of the valley. The first layer of gems intersected with the dragon's plane after 0.75s and the last layer of gems passed this plane 0.75s later. As such, the interface matched the basic and the static interface in terms of timings, but the dynamic nature of this interface made this presentation of the task feel more fast-paced and therefore more challenging.

Participants could see the current point score of each target column at the bottom of the screen as well as a score multiplier, which changed according to the players performance, as shown in Figure 3a. At the end of each trial, the current score was added to the total score and displayed on the screen.

After each block, the participant saw their block statistics, including a breakdown of their points, bonus points and information about their crashes, their highest multiplier and their longest streak of that multiplier. They were then shown the current top 5 high score list with pregenerated entries or their current and previous scores, if higher.

Finally, the participant had the choice to adjust the difficulty level of the following block as per Figure 3b. On higher difficulty levels, the participant encountered a number of obstacles between the targets. These obstacles included a lava wave, which forced the player to move the dragon out of the rest zone, and a spiky gem in one of the target positions. When hit, both the the lava wave and the spiky gem reduced the current multiplier to 1. The spiky gem however had very valuable collectable gems around it as an incentive to just barely avoid the obstacle.

E. Protocol

The experiment comprised a baseline GSR recording, the calibration of the EMG signal, a trial run for assigning participants to the three interfaces, the open-ended task and a final questionnaire. The experimental protocol is depicted in Figure 3c.

For an estimation of the baseline GSR signal, the participant was asked to relax for two minutes. The GSR signal was sampled at 50Hz. Before starting the blocks, we calculated the mean absolute value (MAV) of the EMG signals x over a 750ms window. We calibrated the control signal x_{cal} according to [23] with:

$$x_{cal} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

where x_{min} is the EMG MAV at rest and x_{max} denoted a comfortable contraction, i.e. 10-20% of the maximum voluntary contraction. During the calibration, the participant was shown a simple bar representation of their input signal (see second step in Figure 3c). The calibrated signals x_{cal} were used to control the task. For a right-handed participant, the calibrated signal of the flexor and extensor EMG channels controlled the cursor proportionally along the left and right axis, respectively. For a left-handed participant the channels were reversed.

In the trial run, all participants experienced the basic interface after a brief verbal instruction on the task. The average score of the trial run was used to assign the participant to one of three statistically comparable groups. Specifically, the difference in mean baseline performance was minimized between groups [24]. Groups 1 to 3 continued with the basic, the static and the dynamic interfaces, respectively.

The participants performed the task with the corresponding interface for a voluntary amount of blocks. The experimenter was in the same room seated to the side and behind the participant, outside of the participant's central field of view. They could stop at the end of each block, be it out of boredom or frustration or other reasons. Finally, they were asked to complete an adapted Intrinsic Motivation Inventory (IMI) [26], which quantified four scales, namely "Enjoyment/Interest", "Perceived Competence", "Effort/Importance" and "Pressure/Tension" with varying number of statements. A full list of statements can be found in the **Supplementary Material**. For each statement, the participant indicated their

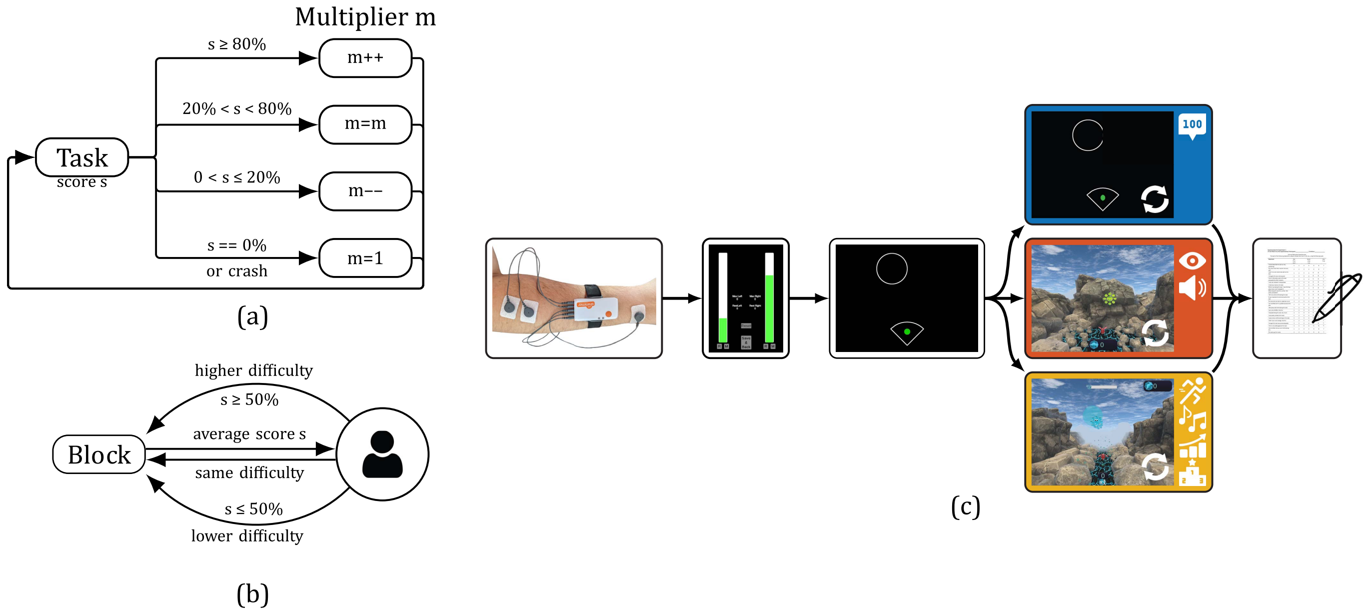

Fig. 3. (a) Multiplier behaviour during the main game loop in the dynamic interface, (b) difficulty choice after each block of the dynamic interface and (c) experimental protocol comprising the setup, the calibration, the trial run, the grouped task and the questionnaire.

agreement on a 7-point Likert scale [27]. Additionally, the participants were asked why they stopped the experiment and whether anything about the task stood out to them, positively or negatively.

F. Analysis

The primary metric used to measure voluntary training time was the time spent in the training in terms of the number of blocks. Furthermore, the average score for each of the subscales of the Intrinsic Motivation Inventory was calculated for each participant and the median taken over these averages for each interface. We estimated muscle fatigue by calculating the the mean frequency of the EMG signal's power spectrum in the last 20 seconds of each block [28]. A linear regression was performed to estimate the trend of the fatigue development. Finally, the reasons for stopping the experiment from each participant were sorted into thematic groups using the thematic framework approach [29].

G. GSR

Due to the nature of this physiological reaction, a response to stimuli only appears 1-3 seconds after the appearance of a stimulus, reaches the peak after another 1-3 seconds and has a half-recovery time of 2-10 seconds [30]. Our task was fast-paced with a target appearing as quickly as every 2.5 seconds. As such our GSR signal were too slow to be meaningful. Currently we are exploring how to better utilise GSR signals. Lack of data from GSRs does not change the outcome of the research presented in this paper.

H. Statistical Analysis

Statistical Analysis was performed in MATLAB (Mathworks, MA, USA). The tests used were Kruskal-Wallis-tests and Mann-Whitney-U-tests between all groups and pairwise, respectively. These non-parametric tests were chosen due to the small sample size of the groups.

TABLE I
OVERVIEW OF THE AGE DISTRIBUTION, THE SEX AND THE PREVIOUS EXPERIENCE WITH MYOELECTRIC CONTROL SCHEMES OF THE PARTICIPANTS IN THE THREE INTERFACE GROUPS

Interface Group	**Age** [y]	**Sex Female/Male**	**Myo Experience Yes/No**
Basic	28.00±1.96	3/1	2/2
Static	27.25±1.49	1/3	1/3
Dynamic	26.75±2.56	2/2	2/2

III. RESULTS

Participants were assigned to the three interface groups according to their performance in the trial run. The median of the individual mean trial run hold scores was 31.88%. Upon assignment, the mean scores were 30.15%, 29.89% and 37.21% in the three groups, respectively, which did not show a significant difference (Kruskal-Wallis-Test, $\chi^2 = 0.27$, $p = 0.8741$, $df = 2$). Table I shows the age distribution, as well as the ratios of the participants' sex and previous myoelectric control experience.

A. Voluntary Training Time as Measurement of Engagement

The voluntary training time was measured by the number of blocks performed by the participants in each interface group after the trial run. We observed a significant difference in the number of blocks between the three interfaces (Kruskal-Wallis-Test, $\chi^2 = 7.09$, $p = 0.0289$, $df = 2$), as shown in Figure 4a. A post-hoc test revealed a significant

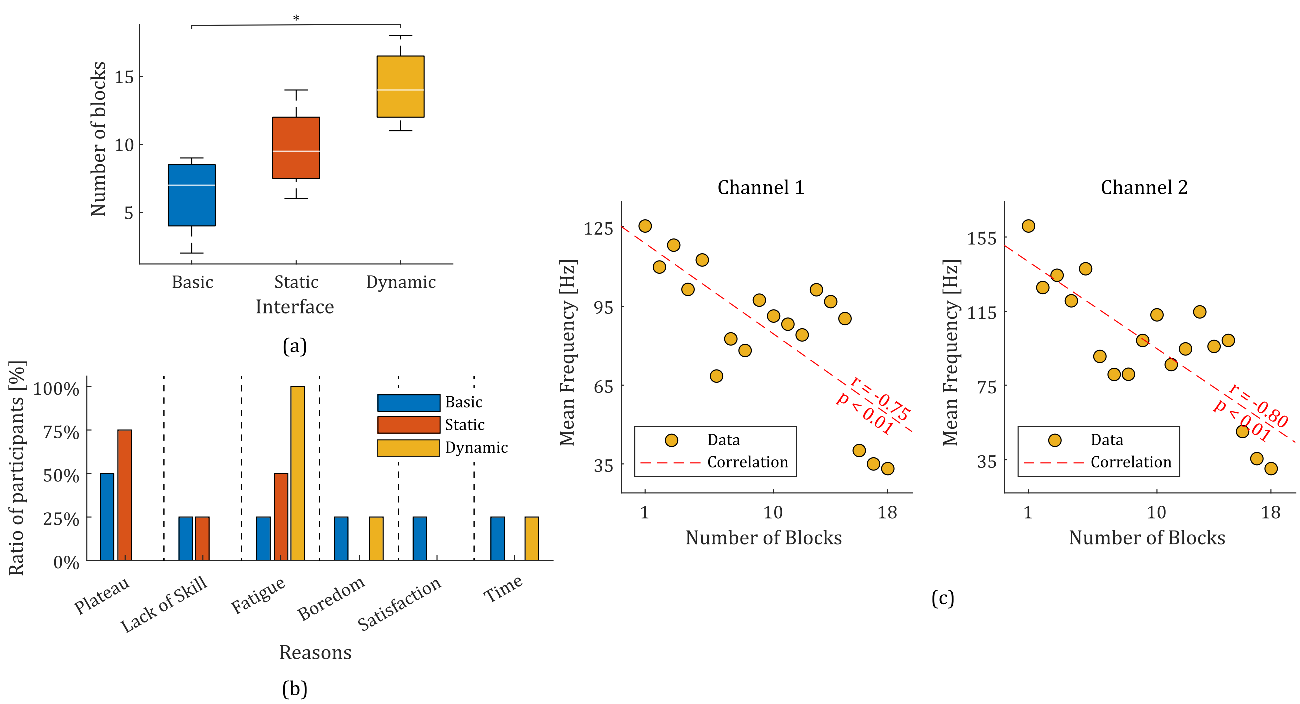

Fig. 4. (a) Distribution of the number of task blocks performed for each interface, (b) number of responses in the shown categories of participants' reasons for stopping the experiment and (c) example of the mean frequency of the power spectrum of one participant's EMG signal for both recorded channels.

difference between the basic and the dynamic interface group ($p = 0.0215$).

B. Reasons for Stopping the Experiment

Participants were asked why they chose to stop playing at the end of the experiment. We categorized their answers into 6 themes, namely a feeling of boredom, a feeling of either muscle or mental fatigue, a perceived lack of skill, the impression that a plateau in performance was reached, satisfaction with the achieved level of performance, and a lack of time. Figure 4b shows the frequencies of the respective results for the different interfaces. Specifically, all participants in the dynamic interface group reported fatigue as the reason for stopping the game, with three people indicating muscle fatigue and the fourth person mental fatigue. Likewise, two participants in the static interface group reported muscle fatigue. We therefore conducted a muscle fatigue analysis to reveal any slowing of the EMG power spectrum, which is a classic signature of muscle fatigue [28]. Four out of the six participants who indicated muscle fatigue as being the primary reason to stop the training showed strong signs of muscle fatigue in at least one EMG channel, **see Figure 1 in the Supplementary Materials**. Figure 4c shows the slowing of the power spectrum, with the progression of blocks, in the EMG data for a representative participant of the dynamic interface group.

C. IMI

Figure 5a shows the medians and standard deviations of IMI scores in all statements belonging to each subscale. The IMI scores of the first subscale, namely Interest/Enjoyment, showed a significant difference between the three interface groups (Kruskal-Wallis-Test, $\chi^2 = 8.25$, $p = 0.0162$, $df = 2$). Removing the outlier clearly visible in Figure 5a does not change the outcome of this test ($\chi^2 = 8.34$, $p = 0.0155$, $df = 2$). Post-hoc analysis revealed that this difference was caused by the significant difference between the IMI scores in interface groups 1 and 2 ($p = 0.0138$). The subscales of Perceived Competence, Effort/Importance and Pressure/Tension did not show any differences between interface groups ($p > 0.05$).

Scores for Perceived Competence showed a positive correlation to the average achieved scores of the participants, independent of interface group ($r = 0.84$, $p < 0.01$) as shown in Figure 5b.

D. Participant Feedback

Furthermore, participants shared their feedback of the task and whether anything stood out positively or negative to them. The results are shown in Table II. All responses were grouped into positive and negative responses as well as suggestions for changes in the software or the presentation.

IV. Discussion

This experiment revealed the positive impact of adopting game design principles in increasing the time that participants engage with a virtual myoelectric training environment voluntarily.

The answers regarding the reasons of the participants for stopping the experiment support the motivational aspects of

TABLE II
PARTICIPANT FEEDBACK DURING AND AFTER THE EXPERIMENT

		Positive	Negative	Suggestions
Basic	Questionnaire	Fun	Difficult	
	During		Boring	
Static	Questionnaire	Enjoyable, Addicting, Sound Effects, Multiple gems per target, Animation, Visuals, Interesting, Fun	Challenging controls, Some lag	Add borders to task space
	During	Sound effects, Addictive potential, Drive to beat own score, Could continue forever		Add upgrades to buy with gems/points earned Add social domain for competition; Interest in maximum reachable score
Dynamic	Questionnaire	Surprisingly satisfying, Enjoyable	Perceived Performance, Music, Too much going on visually	Add tutorial
	During	Would play for longer than base interface, more interesting, more immersion, less focus on arm, scoreboards keep participants motivated	Music, Too much going on visually, occasional glitches	Choice to change/turn off music

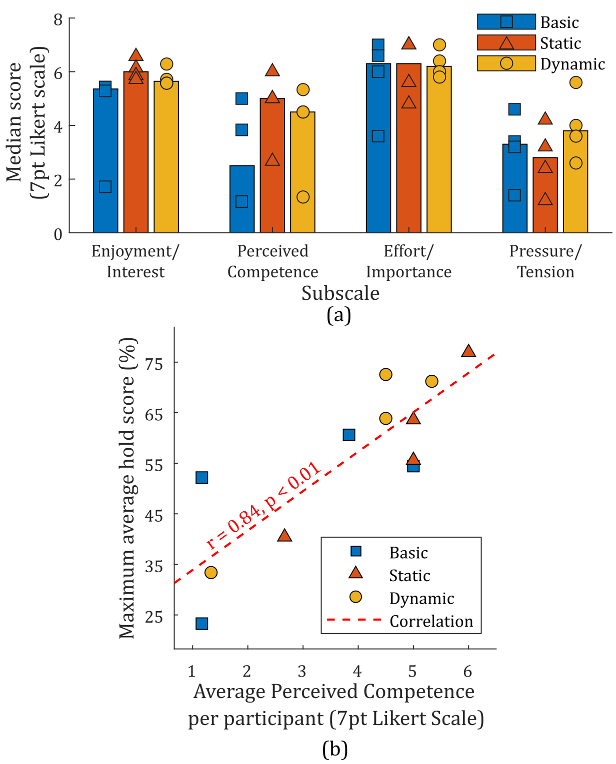

Fig. 5. (a) Median IMI scores for each interface group separated by subscale and (b) participants' highest hold scores plotted against their average score in the *Perceived Competence* subscale.

introducing a task in a game-based interface. Most notably, the responses show a steady increase in the *Fatigue* group over the three interface groups. In other words, participants were more inclined to perform a given task until they felt physical (or mental) tiredness in a game-like environment and were less likely to stop for reasons of boredom or frustration. Furthermore, the feeling that a plateau in skill was reached did not occur in the dynamic interface group, however it did occur in participants of the other groups over a range of individual performances. This is likely due to the game elements introduced that allow the player to reach higher and higher scores when they progress through the training.

Eliciting a feeling of progression throughout the virtual training experience seems to play a role to reduce the feeling of reaching a plateau and therefor the chance of people aborting their training sessions early. However, it is important for the users of the training software not to overexert themselves, as this speeds up the onset of fatigue. This in turn reduces the quality of the EMG signal during training for the participant and the amount of repetitions they are able to perform. Therefore, a clinical use of unsupervised virtual prosthetic training may require a fatigue measure and appropriate feedback.

Two participants stopped the experiment due to a feeling of lacking the skill. This observation highlights that any training interface intended for clinical use should include adjustable difficulty settings to suit the user's individual needs and thereby prolong engagement.

A. User Feedback

The participants' feedback on their respective interfaces gave more insight into what aspects of the training engaged them more and what aspects might have been detrimental to their motivation. A response that gives a clear indicator of why the first group would show shorter training times is that the task was deemed *boring*. However, a repetitive rehabilitation task can get boring even when motivational design elements have been added, as a response of one participant of the dynamic group shows, but this happened notably later in the training.

The change in visual aspects were positively commented on as well as the sound effects. These positive reactions are likely to have led to the increase in the "interest/enjoyment" subscale of the IMI. Considering that the second group show the highest response in that subscale and are significantly different to the first indicates that these aesthetic aspects have a strong influence on the short-term increase in training time. This was further supported by the comments of the interface having "addictive potential" and that they could "continue forever". The choice of a fantastical setting was made for its inoffensiveness and due to positive feedback during the development. The setting was not modifiable in this study for better comparison. However, it could easily be adapted to incorporate a few different settings to cater to individual preferences in further experiments.

In contrast to the sound effects, the music in the third group however was deemed a negative point by one participant, who claimed it made them tense and anxious. Although this was not directly commented on by other participants, this would offer an explanation to the increase in the "pressure/tension" subscale of the IMI. This is generally viewed as a negative predictor of intrinsic motivation [31] and could be part of the reason that the "enjoyment/interest" subscale was slightly lower in the dynamic interface group than the static. However, the number of completed blocks was still considerably higher in the dynamic than in the static interface group. This does not seem to reflect in any of the measure IMI subscales, but the comments during and after the experiment give an indicator as to why this is the case. The main drives to continue playing seem to have been the scoreboards and difficulty progression. The scoreboard showed the participant how they were doing and allowed them to compete against themselves. The difficulty progression reduces the task becoming too monotone, counteracts the onset of boredom and gives the participant a feeling of accomplishment as well as access to higher scores. These two game elements strongly feed into the motivational principle of "challenge" [11], [17] and with this in mind the participants comments support these as the strongest driving forces for the longer training time.

B. IMI

The IMI was developed in 1982 [26] and has since been used in various fields from sports over medicine to computer tasks [32]. As a self-report measure for motivation it was used in the field of virtual prosthetic training [33], [34], [35]. Therefore, we hypothesized that it could give us an indication of what aspects of the the participants' motivation is enhanced by the game and therefore leads to a higher engagement. The results show however that in this case the IMI was not sensitive enough to provide a clear outcome. This might be that the IMI alone is not enough to tease out the different influences that the game design elements have on the participants. The number of participants and the fact that they did not experience all interfaces to compare them could have led to results that are difficult to compare.

Despite that, the IMI showed some interesting results. The generally high results in the "enjoyment/interest" subscale are likely due to the novelty of the task for many participants. However, even after more repetitions of virtually the same task, the significantly higher results in this subscale for the game-based versions indicates a positive effect of the game design past the novelty. Additionally, the participants' perception of their competence of the task was correlated with their actual performance, irrespective of the different types of feedback that was given in the different interface groups.

Furthermore interesting is the fact that all three groups reported almost the same amount of perceived effort and importance they put into performing the task well, even after sometimes vastly different amounts of time spent in the task. The generally high levels of effort could be caused by the fact that it was an experiment and everybody was motivated to help with the research. However, the similarity of the results over very different lengths of performance support the results that the participants are more likely to play until they notice physical signs of fatigue with the game-based versions. This might be caused by a reduced perception of strain per task-block than when performing the base interface due to a stronger immersion into and engagement with the game.

V. Conclusion

The use of myoelectric prosthetic hands typically entails lengthy training in specialised clinics. This could be alleviated by supplementing the regimen with a virtual prosthetic training in the home environment. This proof-of-principle study shows that for virtual training environments, implementing game design principles can be beneficial to the voluntary training time of the trainee, counteracting potential boredom or frustration with the often tedious and repetitive exercise.

The most prominent game design elements identified in this investigation were: a more interesting sensory experience through visuals and audio, a scoring system that encourages the user to compete against one's own scores and potentially others, and a progression or change in the exercise that keeps it from feeling repetitive and can lead to higher scores. These elements are not specific to the type of game used in this research and can be used in a similar fashion in various other game formats. They need to be tailored to the type of game at hand, as the same kind of scoring for instance might not be sensible in different games. The more important point is that the underlying game design principles are incorporated to enhance the experience for the user.

Elements like the ones discussed above will have to be investigated for their long-term effects on the enhancement of engagement in a virtual training task and will ideally be tailored to the users' preferences. As the static interface had slightly higher results in two of the motivation subscales, it would be beneficial to add the game elements used in the dynamic interface one by one to extract which elements have the most positive impact on the motivation. Additionally, purely aesthetic choices could be made optional or adjustable to meet the individual user's preferences.

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