Effects of Haptic Feedback on User Perception and Performance in Interactive Projected Augmented Reality

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ABSTRACT

By means of vibrotactile and force feedback, i.e., haptics, users are given the sensation of touching and manipulating virtual objects in interactive Extended Reality (XR) environments. However, research towards the influence of this feedback on the users' perception and performance in interactive XR is currently still scarce. In this work, we present an experimental evaluation of the effects of haptic feedback in interactive immersive applications. By means of a Projected Augmented Reality (PAR) setup, users were asked to interact with a projected environment by completing three different tasks based on finger-tracking and in the presence of visual latency. Evaluations were performed both subjectively (questionnaire) and objectively (i.e. duration and accuracy). We found out that while haptic feedback does not enhance the performance for simple tasks, it substantially improves it for more complex ones. This effect is more evident in presence of network degradation, such as latency. However, the subjective questionnaires showed a general skepticism about the potential of incorporating haptic information into immersive applications. As such, we believe that this paper provides an important contribution toward the understanding and assessment of the influence of haptic technology in interactive immersive systems.

CCS CONCEPTS

• **Information systems** → *Multimedia streaming*; • **Human-centered computing** → **User studies**; **Usability testing**; *Laboratory experiments*; **Mixed / augmented reality**; **Haptic devices**; • **Computing methodologies** → Motion capture; **Mixed / augmented reality**.

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KEYWORDS

Haptic Feedback, Projected Augmented Reality, User Perception, User Performance, Interactive Extended Reality, Visual Latency

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1 INTRODUCTION

Augmented Reality (AR) is gaining attention in multiple fields of society, as it is considered the future of human-to-human and human-to-machine interactivity. While it started only as an asset for entertainment, e.g., gaming (*e.g. Pokémon Go*[1]), Extended Reality (XR) in general and AR, in particular, are slowly taking their place in other societal domains, such as in industry (Industry 4.0), healthcare (telesurgery) and education (remote learning) [12].

In its current form, AR provides a virtual overlay to real-world objects[1]. Thus, it is mostly limited to the visual interaction with the virtual environment, where the other senses are seldomly addressed. Preliminary results in literature [7] do claim, however, that the introduction of tactile feedback has a positive influence on both the subjective perception of presence and influence and objective, task-related performance of end-users in immersive XR environments. This tactile feedback could be provided by means of kinesthetic simulation (*i.e.* movement and force), skin deformation, and vibration [4]. However, little is known about the influence of haptic feedback regarding the interaction with an AR overlay and how it changes the user's performance and perception in terms of the learning curve of a set of predetermined tasks as well as in the presence of network impairments, as it would happen with networked XR.

The limited research that does exist for the inclusion of haptics in AR environments is scattered over a wide range of applications such as rehabilitation[9], remote collaboration[13], and

[1]https://www.pokemongo.com/en-us/

virtual training[3]. These studies tend to conclude a positive influence of haptic feedback in AR environments in terms of completion time[3, 7, 9], accuracy[3], user experience[13], and interaction[11]. However, to our knowledge, these experiments are very limited in terms of general applicability and do not take into account the possible effects of networks on the experience and interactivity, which is the purpose of this work.

In this paper, we aim to explore the effects of haptics on the overall perception and performance of users of interactive immersive applications by means of a subjective (perception) and objective (performance) study. A task-based Projected Augmented Reality (PAR) system setup was created, where haptic feedback was integrated in the form of vibrations around the wrist by means of a set of haptic gloves, and network impairments were introduced in the form of end-to-end latency. Through three different tasks, we conducted a user study comparing cases with haptic feedback (group B) and without (group A) in terms of both duration and accuracy as well as subjective, perception-assessing questionnaires. We found out that while haptic feedback does not enhance the performance for simple tasks, it substantially improves it for more complex ones. This effect is more evident in presence of network degradation, such as latency. However, the objective assessment not always aligns with subjective perception, as shown by the subjective questionnaires. In them, participants were rather skeptical about the potential of incorporating haptics into immersive applications.

The remainder of this paper is organized as follows. Section 2 gives a brief overview of other studies related to the effects of haptics on immersive applications. In Section 3 the test setup, game characteristics, and objective/subjective methodology are presented.Section 4 describes the most prominent findings. Section 5, at last, summarizes this paper by listing the most important conclusions that can be drawn from this study.

2 RELATED WORK

A limited amount of approaches exist that aim to provide an answer to the effects of haptics on the overall perception of interactive XR applications. *Ocampo et al.* [9] evaluated the case of robotic rehabilitation exercises. They investigate both the difference between Virtual Reality (VR) and AR and the influence of the absence/presence of haptic feedback. The combination of spatial AR and haptics showed the best results in terms of task completion time for users undergoing cognitive loading.

Wang et al. [13] showed a VR/Spatial Augmented Reality (SAR) remote collaborative system that provides haptic feedback with tangible interaction between a local worker and a remote expert helper. Based on a within-subject user study to compare two interfaces for remote collaboration (i.e. one with Mid-air Free Drawing (MFD)) and one with Tangible Physical Drawing (TPD)). Users felt that the TPD interface supporting passive haptic feedback could significantly improve the remote experts' user experience in VR.

Pezent et al. [11] explored haptic feedback on the wrist for interacting with virtual objects. To this end, they used *Tasbi*, a compact bracelet device, capable of rendering complex multisensory squeeze and vibrotactile feedback. Based on their findings, wrist-based haptics does substantially improve virtual hand-based interactions in AR/VR compared to no haptic feedback.

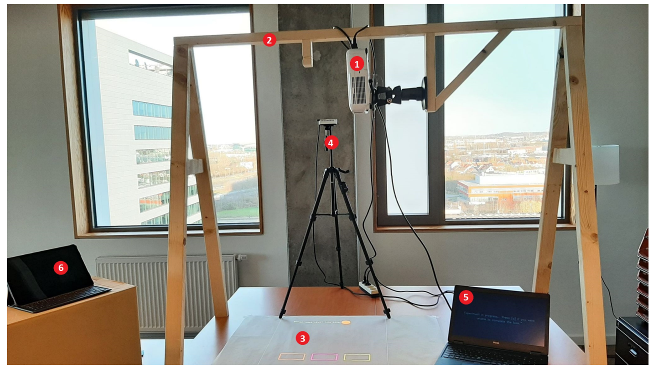


Figure 1: Setup created for the study. It consists of the projector (1), the wooden frame (2), the projection canvas (3), the depth camera (4), the instruction laptop (5), and the questionnaire tablet (6).

Collaço et al. [3] performed an experimental study for VR dental training, in which a comparison with and without haptic feedback was made. Their results show that immersion positively impacts the training w.r.t execution time, needle insertion point, and insertion accuracy, as well as the sense of syringe control and haptic feedback.

Kreimeier et al. [7], at last, examined the influence of different types of haptic feedback on presence and performance regarding three different tasks in VR. To this end, 14 subjects were gathered who performed throwing, stacking and object identification tasks only visual feedback, vibrotactile feedback or force feedback. Their results show that vibrotactile feedback outperforms both visual and force-feedback regarding induced feelings of presence in test subjects. Furthermore, force feeback tends to show a significant influence in terms of execution time for certain tasks when compared to both visual and vibrotactile feedback.

The above overview of related research shows that there is no clear consensus yet on both the benefits of interactive AR environments and haptic feedback in comparison with VR and non-haptic systems. Therefore, we believe that this work proves to be a valuable addition to new insights into this topic.

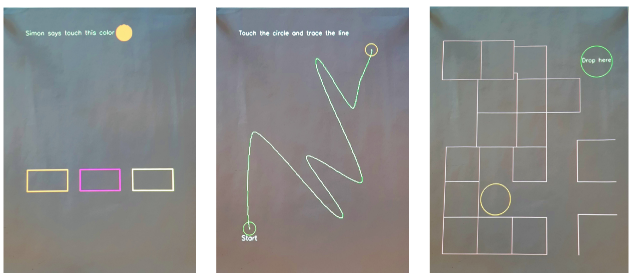
3 A PROJECTED AUGMENTED REALITY HAPTICS-ENABLED EXPERIMENTAL EVALUATION

This Section presents the methodology for the evaluation of the impact of haptics on PAR. First, Section 3.1 provides a technical description of the setup (Figure 1). Second, Section 3.2 introduces the tasks to be performed. Finally, Section 3.3 describes the procedure followed for the subjective and objective user study.

3.1 Technical setup

The PAR setup can be seen in Figure 1. It is composed of seven elements, namely a projector (*Epson EB-S05*[5]), a wooden frame, a projection canvas, a depth camera to perform finger tracking, a laptop (for instructions running of the different games and objective metrics logging), a questionnaire tablet, where the users could

Figure 2: The Noitom Hi5 VR haptic gloves.



(a) Simon Says **(b) Trace The Line** **(c) Obstacle Course**

Figure 3: Visualization of each of the three test scenarios.

complete the questionnaires pre-, post-, and in-session, and a pair of haptic gloves for feedback.

The finger tracking is conducted by an *Intel RealSense D435*[6] depth camera, placed on a tripod behind the canvas. Before the start of the experiment this finger tracking module, implemented in *Python* using the *OpenCV* library[2], is configured with the color of the trackers and the current light conditions. This is done by first projecting a black screen on the canvas for the color values to be read by the depth camera. Next, one of the trackers (a blue paper) is placed in the middle of the canvas after which the color values are read once again by the depth camera. Based on the difference between the two images, the Hue-Saturation-Value (HVS) color range is determined. During the actual experiment, a mask is created for each frame by identifying the pixels laying within this predetermined HVS range. After consecutive morphological opening and closing of this mask, every connected blob of pixels is identified as a tracker of which the centroid is calculated for further processing. By including the RealSense's depth information, touches, hovering, and more can be identified. These processing steps can be performed within a time interval of at most 250 ms while maintaining a framerate of 20 fps.

Haptic feedback is provided by *Noitom's Hi5 VR gloves*[8] (Figure 2) in the form of vibrations around the wrist. These gloves communicate wirelessly with a USB dongle connected to the instructions laptop. As the Hi5 gloves cannot be directly controlled from the main Python application, a small Unity plugin was developed in C# which communicates with both the gloves and the

[2]https://pypi.org/project/opencv-python/

Table 1: Overview of the subjective questions being asked to each group pre-, post-, and in-session.

Timing	Group	Question
Pre	Both	• Handedness, Age, Gender • Ishihara tests • Prior experience with PAR, haptics (None, Once, Quite, Very) • Number of prior subjective evaluations (First, 1-5, 5+) • Technical proficiency (Low, Medium, High)
In	Both	• During the last experiment (first of the main phase), I perceived latency between my own physical movement and the visual events on the screen (1 (not at all) to 5 (a lot))
Post	Both	• [For each game] I found the task easy to complete (1 (Strongly disagree) to 5 (Strongly agree)) • [For each game] I was given sufficient instructions to complete this task (1 (Strongly disagree) to 5 (strongly agree)) • [For each game] It was difficult for me to concentrate on the task (1 (Strongly disagree) to 5 (strongly agree))
	A	• [For each game] Do you think the addition of haptic feedback in the form of vibrations (i.e. low-intensity and low-frequency when right; high-intensity and high-frequency when making an error) would decrease the number of errors you made while completing this task? (1 (Strongly disagree) to 5 (strongly agree)) • [For each game] Do you think the addition of haptic feedback in the form of vibrations would decrease the duration of completing this task? (1 (Strongly disagree) to 5 (strongly agree)) • [For each game] Do you think the addition of haptic feedback in the form of vibrations would make the interaction with this task more natural and intuitive? (1 (Strongly disagree) to 5 (strongly agree))
	B	• [For each game] Do you think that the addition of haptic feedback in the form of vibrations decreased the number of errors you made while completing this task? (1 (not at all) to 5 (a lot)) • [For each game] Do you think that the addition of haptic feedback in the form of vibrations decreased the duration of completing this task? (1 (not at all) to 5 (a lot)) • [For each game] Do you think the addition of haptic feedback in the form of vibrations made the interaction with this task more natural and intuitive? (1 (Strongly disagree) to 5 (strongly agree))

main application through push/pull sockets in *ZeroMQ*[15] to trigger haptic vibrations whenever needed. As such, the gloves are configured to vibrate repeatedly for 200 ms, followed by a 2s pause as long as the subject is performing the right, expected actions. Whenever the users make a mistake, they feel a repeated 500 ms vibration followed by a 1s pause.

3.2 Test scenarios

In order to evaluate the influence of haptic feedback on user performance and perception, three PAR games were prepared: *Simon Says*, *Trace The Line* and *Obstacle Course* (Figure 3). First, in *Simon Says* [10], users have to push a button after which they are given a target color and three different color options. Users should attempt to select the target color out of the given options as fast as possible (where the timer starts once the start button is pressed) in 5 consecutive rounds. When a wrong color is selected, one error is counted. Users are given visual feedback as the selected button turns green in case the right color is selected and red otherwise.

Second, in *Trace The Line*, users are given a random line with a start and an endpoint. Users should try to follow the presented trajectory with one finger as fast and accurately as possible, where the timer starts once the start point is pressed. An error is counted every time the distance between the user's finger and the target line exceeds a predetermined threshold of 10 pixels. This is also visually displayed by coloring the line in red (instead of green) as long as the threshold is surpassed.

Finally, for *Obstacle Course*, users have to guide a deformable circle through a maze towards a drop point as fast and accurately as possible. This can be done by pinching and rotating the circle in an appropriate manner. Time is recorded from the first time the circle is touched, and an error is counted every time the circle exceeds the borders of the maze. Visual feedback is provided by coloring the according part of the maze in red every time this happens. In addition, the deformable circle colors orange instead of yellow whenever touched.

Each of the games can also be configured to include a certain visual latency, i.e. the events projected on the screen happen a certain amount of time after the actual physical movement of the user. As such, it is possible to investigate whether the addition of haptic feedback helps to overcome the shortcomings that could be derived from lower network performance.

3.3 Test procedure, subjective, and objective evaluation

Every experimental session is divided into two subsequent phases. First, in the training phase, the subject tries each of the three games to get familiar with them. No data is recorded. Second, in the main phase, each of the three games is played four times. In each of these iterations, one game and one possible network latency are randomly selected, but such that every (*game*, *latency*)-combination has been visited once by each subject. The possible latencies are 0.0s, 0.5s, 1s, and 2s.

During the session, both objective performance measurements and subjective evaluations were taken. The objective metrics being measured are (i) duration and (ii) errors. First, *duration* is the time it takes to complete each task. For *Simon says*, this time is defined

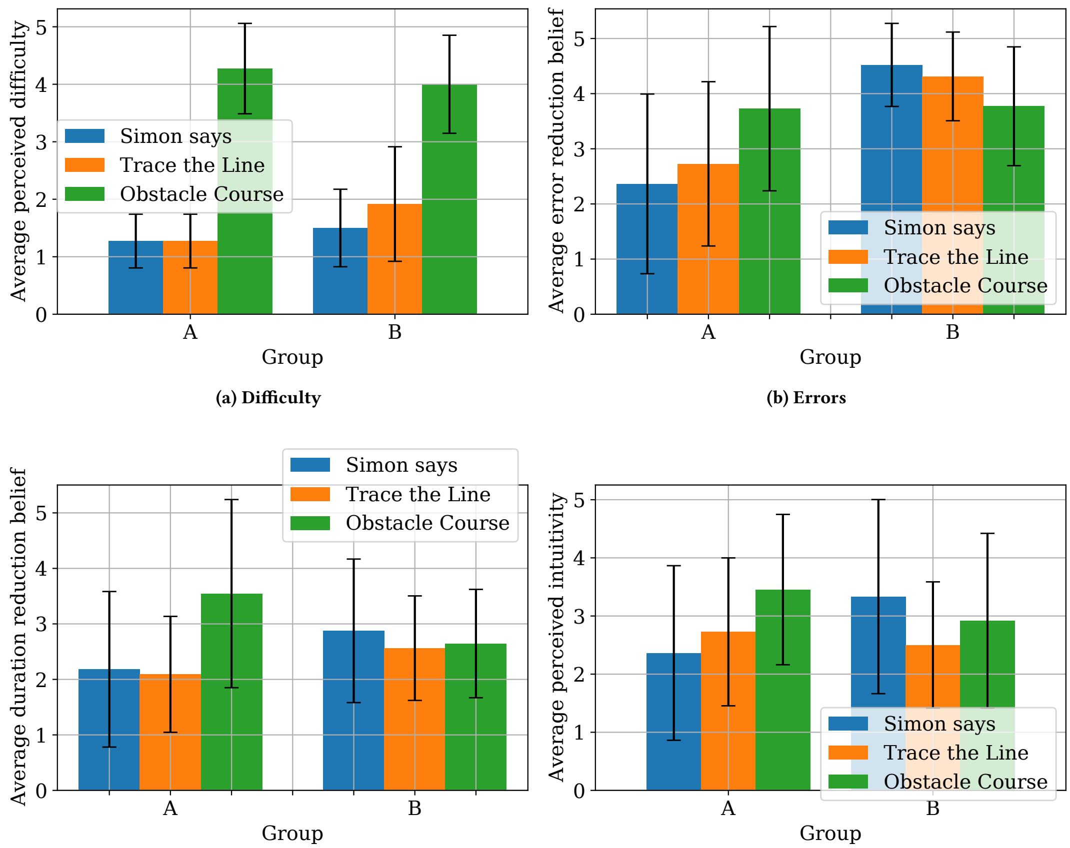
Table 2: Descriptions and demographics of the 23 participants of the study.

Gender	6 female (26.1%), 17 male (73.9%)
Handedness	19 right (82.6%), 4 left (17.4%)
Age	Between 19 and 44, 26.3 average and 26.0 median.
Technical proficiency	9 high (39.1%), 3 medium (13.0%) and 11 low (47.9%).
PAR experience	2 quite (8.7%), 6 once (26.1%) and 15 never (65.3%).
Haptics experience	2 quite (8.7%), 7 once (30.4%) and 14 never (60.9%).
Experience with subjective tests	3 did 5+ (13.0%), 9 did 1-5 (39.1%) and 9 never (39.1%).

as the time between the first hovering over the start button and the pressing of the last color button (after 5 iterations). For *Trace The Line*, it is the time between the first press of the start button and the first touch of the finish point. Finally, in *Obstacle course*, it reflects the time between the first touch of the circle and the first instant that the circle sufficiently overlaps with the drop zone. Second, the *errors* metric is the number of mistakes a subject makes within each task. In *Simon says* it is defined as the number of times a subject presses the wrong color over the five iterations within each instance of the game. In *Trace The Line*, it counts the number of times the user's finger moves further than a predetermined margin away from the target line. For the *Obstacle course*, it reflects the number of times the edges of the labyrinth were touched by the circle. It is worth noting that all participants were informed about these objective assessments prior to the experiment.

In terms of subjective evaluations, subjects were also asked to fill in a pre-, in-, and post-session questionnaire (Table 1). The pre-session questionnaire is the same for both groups and polls about handedness, age, gender, correct color vision, technical proficiency, and prior experience with PAR, haptic technology and subjective evaluations in general. The in-session questionnaire (during the main phase) consists of one questions after each game in which both groups are asked to assess the perceived latency between their own physical movement and the visual events on the screen on a 1-5 scale. Post-session, group A was given 3 additional questions for each game asking them whether they expected the hypothetical addition of haptic feedback to be beneficial in terms of task duration, error reduction, and intuitivity (1-5 scale). Group B was asked in three similar questions whether they actually perceived the haptics to have a beneficial impact on these same three aspects (1-5 scale).

In summary, a session takes 12 iterations of the games (4 per game) in random order and with random latency, but such that every (game, latency)-pair is presented once to each subject. Each participant answers a pre-session questionnaire, 1 or 3 question(s)



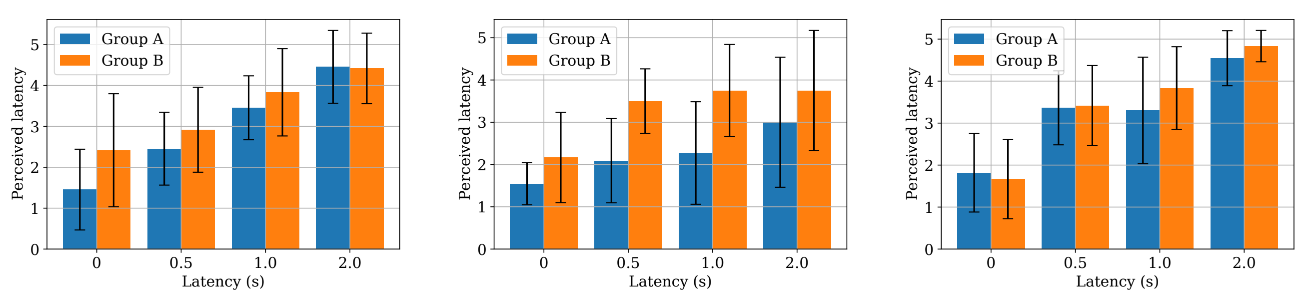
(a) Difficulty

(b) Errors

(c) Duration

(d) Intuitivity

Figure 4: Average subjective belief regarding the influence of the haptics on difficulty, errors, duration and intuitivity for the three games, split per group, on a 1-5 scale as collected from both the post- and in-session questionnaires. The error bars indicate one standard deviation.



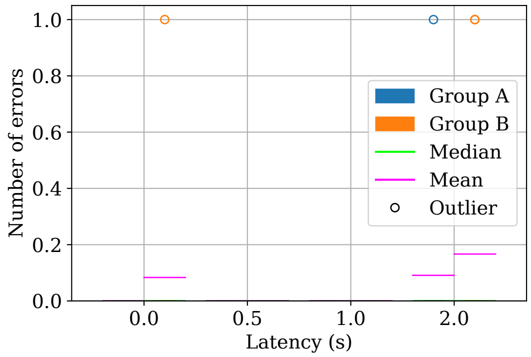
(a) Simon Says

(b) Trace The Line

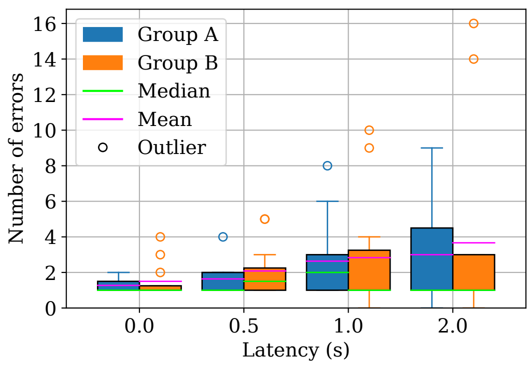
(c) Obstacle Course

Figure 5: Objective (s) vs. subjectively perceived (1-5 scale) latency for each of the games and per group. The error bars indicate one standard deviation

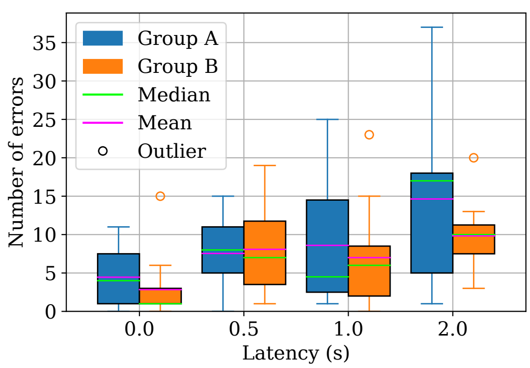
after each iteration (depending on the group) and one post-session questionnaire. It amounted to roughly 20-25 minutes per participant. To stimulate the performance of the participants, in terms of speed and accuracy, a free movie ticket was promised to the person that tops the combined ranking of playing time and number of errors in each group.



(a) Errors, Simon says

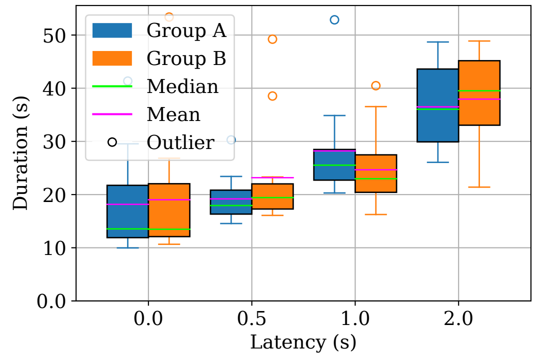


(b) Errors, Trace the line

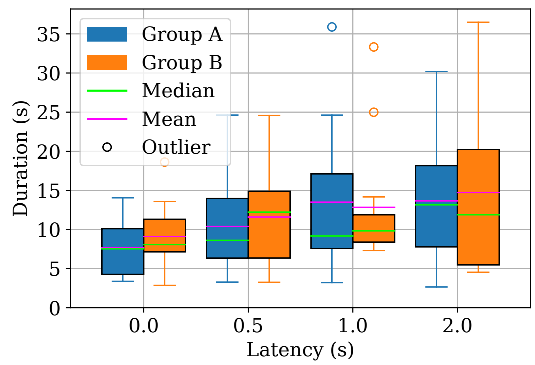


(c) Errors, Obstacle course

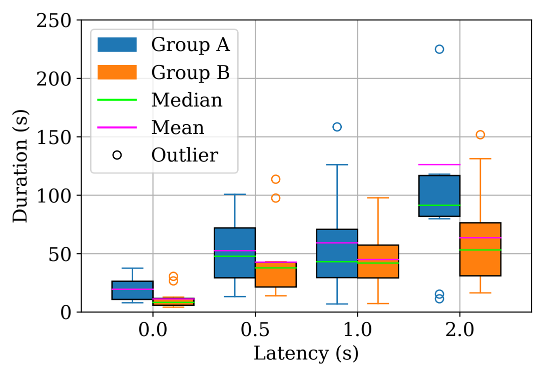
Figure 6: Boxplots of the objectively measured number of errors for each game, as a function of the latency and split per group. Outliers are defined as samples laying outside the interval $[Q1 - 1.5 \cdot \textbf{IQR}, Q3 + 1.5 \cdot \textbf{IQR}]$, with IQR $= Q3 - Q1$.



(a) Duration, Simon says



(b) Duration, Trace the line



(c) Duration, Obstacle course

Figure 7: Boxplots of the objectively measured duration (s) for each game, as a function of the latency (s) and split per group. Outliers are defined as samples laying outside the interval $[Q1 - 1.5 \cdot \textbf{IQR}, Q3 + 1.5 \cdot \textbf{IQR}]$, with IQR $= Q3 - Q1$.

3.4 Participants descriptions and demographics

23 subjects were gathered for user testing. As a result of the pre-session questionnaires, the distributions reported in Table 2 were obtained. In addition, they were tested for correct color vision using Ishihara tests[14]. In order to provide a consistent benchmark, participants in these tests were to be split into two groups: group A (without haptics) and group B (with haptics). Participants of the control group performed the tasks without wearing a haptic glove, while participants of the test group took part in the evaluation wearing it. The subjects were evenly and randomly assigned to one of the two groups. As a result 11 subjects (Group A) performed the

experiment only by means of visual feedback, while 12 subjects (group B) were provided with haptic feedback as well.

4 RESULTS

This section presents the results of the subjective and objective evaluation. First, Section 4.1 discusses the perception analysis. Then, Section 4.2 focuses on the performance results.

4.1 Influence on subjective user perception: difficulty, intuitivity, duration, error rate and network latency

Figure 4 presents the output of the subjective evaluations for both groups based on the questions presented in Table 1. First, in terms of perceived difficulty (Figure 4a), it can be noticed that the *Obstacle course* game is perceived as rather difficult for both groups compared to both *Simon says* and *Trace The Line* ($p < 0.05$ for both comparisons and in both groups). This observation allows us to interpret further results in the light of straightforward vs. more complex tasks. Furthermore, *Trace The Line* is perceived as slightly more difficult by group B than by group A ($p < 0.05$). As a large majority of the subjects (91.3%) indicated to have used haptic technology at most once before, it can be assumed that unfamiliarity with the technology plays an important role in this finding. Second, for the error rate (Figure 4b), subjects in group A seem to have lower expectations regarding influence of haptics for the games perceived as the least difficult (*Simon says* and *Trace the Line*) than what was actually perceived by using the haptics by group B ($p < 0.05$). These results should be interpreted with care, however, as the unfamiliarity with haptics of the subjects in group A makes it rather difficult to assess the possible benefit of including vibrational feedback. Finally, for *Obstacle Course*, no significant difference between expectations and perception can be distinguished. Fourth, in terms of perceived duration improvement and intuitivity (Figures 4c and 4d), no strongly significant differences between both groups were concluded ($p > 0.05$).

Based on the answers to the in-session questionnaires, the perceived latency (on a 1-to-5 scale) for each of the groups can be compared with the actual latency on the visuals (in ms) (Figure 5). In general, the presence of haptics either has little to no effect (*Obstacle Course* and *Simon Says*) or a negative effect on the perception of latency (*Trace the Line*, $p < 0.05$). For the latter, group B (with haptics) consistently rates the perceived latency higher than the actual one. This is an intuitive effect, however, as it could be expected that zero-latency haptic feedback would emphasize any visual latency in the system as haptics and visuals would not be synchronized. In this case, however, a more pronounced expression of this effect could be expected in the *Simon Says* game, as pressing buttons allows for a straightforward manner of revealing desynchronization. As the perception of latency is highly entangled with feelings of immersiveness in such multimodal systems, this is an interesting finding as it points out that in some cases the addition of haptics might even decrease immersiveness rather than improve it [2].

4.2 Influence on objective user performance: duration and error rate

As previously introduced, during the sessions participants were objectively monitored on duration and error rate in function of the added latency. The results can be seen in Figures 6 and 7. It is interesting to see that for the two games perceived as the least difficult (*Simon says* and *Trace The Line*) the addition of haptics brings no significant improvement in terms of error reduction ($p = 0.17$ and $p = 0.25$, respectively). Here, it has to be noted that the nature of the *Simon Says* game induces little errors, such that comparing is difficult. For the same reason, no boxplots are drawn in Figure 6a as every non-zero value is identified as an outlier. In terms of duration, group B also did not show a significant improvement for these two games (Figures 6a, 7a, 6b, and 7b). For the *Obstacle course* game (Figures 6c, 7c), which was perceived as the most difficult, the addition of haptic feedback clearly decreases the users' duration ($p < 0.05$). This effect is especially remarkable for worse conditions (i.e., larger latency). For a 2s latency, for instance, group B even manages to complete the game about twice as fast as group A (126.2 s vs. 63.6 s) on average. Moreover, group A makes on average 4 errors more than group B. Surprisingly, this contradicts the subjects' beliefs as group B is clearly having higher perceptions in terms of error reduction for *Simon Says* and *Trace The Line*, which is not reflected in the objective measurements. Moreover, users in group B did not show a significantly higher perception in terms of duration for the *Obstacle Course* while objectively speaking, this clearly is the case. A possible explanation is once again the lack of experience with haptics in most subjects.

5 CONCLUSION

In this work, we have presented a study of the effects of haptics on the perception and performance of tasks in interactive PAR. We have found out that haptic feedback reduces the execution time of the user on tasks perceived as more difficult. This effect is enhanced as the network conditions worsen. However, this is not reflected in the subjective beliefs of the subjects. Furthermore, it was shown that for one of the tasks, latency was consistently perceived higher in the haptic group than in the non-haptic group. This is an interesting conclusion, as it points out that the addition of haptics can for certain tasks increase the awareness to reduced network performance. This is a very relevant result for future complex immersive interactive applications, such as immersive surgery, where the inclusion of haptics is currently researched.

In terms of future work, it would be interesting to see how these results scale to larger user studies with a higher variety of tasks in terms of actions and difficulty. Furthermore, user perception of haptics could be studied more in depth by including physiological measurements such as Electroencephalograms (EEG) or heart rate into the setup.

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