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Immersive Virtual Environments for Upper-Limb Robotic Rehabilitation

Salvatore L. Cucinella[1,2], Job L.A. Mulder[1], Joost C.F. de Winter[1], and Laura Marchal-Crespo[1,2(✉)]

[1] Department of Cognitive Robotics, Delft University of Technology, Delft, The Netherlands
l.marchalcrespo@tudelft.nl

[2] Department of Rehabilitation Medicine, Erasmus University Medical Center, Rotterdam, The Netherlands

Abstract. Neuroscience evidence suggests that personalized, task-specific, high-intensity training is essential for maximizing recovery after acquired brain injury. Robotic devices combined with immersive virtual reality (VR) games, visualized through head-mounted displays (HMDs), can support such intensive training within naturalistic virtual environments with audio-visual stimuli tailored to individual needs. However, the impact of these auditory and visual demands on cognitive load remains an open question. To address this, we conducted an experiment with 22 healthy participants to explore how varying levels of visual, auditory, and cognitive demands affect users' cognitive load and performance during a shopping task in immersive VR. We found that mental demand had the most significant impact on increasing cognitive load and hampering task performance. Visual demands, although affecting gaze behavior, did not significantly affect cognitive load or performance. Auditory demands showed small effects on cognitive load.

1 Introduction

Every year, millions of stroke survivors lose their functional autonomy, posing a tremendous societal and economic challenge. Clinical evidence suggests that patients should engage in personalized, task-specific, high-intensity training to maximize the recovery of their lost functions. Robotic devices combined with immersive virtual reality (VR) games visualized through head-mounted displays (HMD) can support intensive training within an engaging naturalistic visualization of virtual environments (VE) that can be adapted to the individual's needs. Yet, it is still an open question how these immersive virtual environments should be designed to maximize patients' recovery [1].

HMDs can provide a naturalistic visualization by incorporating stereovision and avatars that reduce the cognitively demanding visuospatial transformations

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between the performed movement and its visualization, contrary to conventional flat screens. In a recent study with twenty older participants and five sub-acute brain-injured patients who trained with the assistance of an exoskeleton, we showed that HMDs improve the quality of reaching movements and reduce cognitive load compared to conventional computer screens. Importantly, participants rated HMDs as highly usable despite their non-familiarity with the technology, encouraging their use in neurorehabilitation [2].

An important benefit of the immersion achieved with HMDs is that it is possible to control the visual information provided to the user, which might impact their psychological states, e.g., motivation and attention. In a recent experiment, we explored the impact of visualizing (or not) rehabilitation robots in VR on motivation, presence, embodiment, and attention, while healthy participants were supported (or not) in performing upper-limb activities [3]. The underlying assumption was that the visuo-haptic sensory conflict from feeling assistance but not seeing the assisting robot (contrary to real-life settings) would impact their user experience. Yet, we found that robot visibility did not significantly affect any psychological measures. Remarkably, most participants did not notice the difference in the robot visibility, raising the question of whether manipulating the virtual environment might indeed impact psychological states, e.g., cognitive load.

To address this question, we ran an experiment to explore how low and high levels of visual, auditory, and cognitive demands affect users' cognitive load and performance when performing a shopping task in immersive VR. We decided to first involve only healthy participants rather than directly overloading patients and therapists performing exploratory experiments. In the following, we present an overview of the experiment and preliminary results.

2 Methods

Twenty-two young, healthy participants (11 females, 11 males) were immersed in a virtual supermarket using an HMD (HTC VIVE Eye Pro, HTC, Taiwan & Valve, USA). They performed a virtual shopping task, which consisted of reading a list of 30 products, reaching and picking the listed products in the given order using the HMD controller with their right arm and placing them in a shopping cart. They could revisit the shopping list at any moment. They were reminded not to rush and that it is unlikely that all 30 items could be completed within the session.

Participants performed the shopping task under seven randomly presented conditions of 120 s each:

- Baseline: Empty supermarket.
- Visual Low: Characters performing typical supermarket actions (e.g., walking behind the shelf) were added.
- Visual High: Characters with abnormal appearances (e.g., Vikings) and two ceiling alarms added (Fig. 1).

Fig. 1. The task environment from a remote perspective during the visual high condition with characters surrounding the main shelf.

- Auditory Low: Normal supermarket sound (e.g., footsteps, checkout bleeps, crowd conversations) added.
- Auditory High: In addition to the normal sounds, we added short incidental sounds, e.g., police sirens, running footsteps behind the participant, and bottles falling.
- Mental Low: A 0-back secondary task was added, i.e., participants heard an auditory voice that gave 4 sets of random single-digit numbers and were required to repeat the number they had just heard.
- Mental High: Participants were asked to repeat out loud the number they had heard two numbers ago.

We assessed participants' cognitive load using the weighted NASA Task Load Index (NASA-TLX) questionnaire and psychophysiological measures known to be linked to cognitive load, such as heart rate (measured using a Biotrace, Mind-Media, NeXuS-4) and heart rate variability, defined by the root mean square successive difference (RMSSD) of the RR intervals. We further analyzed participants' gaze behavior using the built-in eye-tracking system of the HMD to determine the total time spent looking at several areas of interest, namely, the main shelf, cart, shopping list, or other objects. Finally, task performance was calculated as the number of products placed in the cart per minute.

We analyzed the data using Linear Mixed Models in R-Studio (R version 4.3.1), with independent variables *condition* (baseline, visual low/high, auditor high/low, and mental high/low) and *order* of the conditions (from one to seven), with the participant ID as a random effect. Posthoc analysis was performed to compare all visual, auditory, and mental conditions to the baseline condition using Holm's correction. Cohen's d was used as an effect size metric. The significant level was set to $p < 0.05$.

3 Results

The condition that resulted in the most evident differences w.r.t. baseline was the mental high condition. In particular, we found a significant increase in the NASA-

TLX scores (Fig. 2, $d = 4.82$, $p < 0.001$), the gaze duration on the shopping list ($d = 1.31$, $p < 0.001$) and on the main shelf ($d = 1.48$, $p < 0.001$). We also found a significant deterioration in task performance ($d = 3.21$, $p < 0.001$). The mental low condition also resulted in a significant increase in the NASA-TLX (Fig. 2, $d = 1.45$, $p < 0.001$) and the gaze duration on the shopping list ($d = 0.74$, $p = 0.038$) w.r.t. baseline.

Regarding the visual low and high conditions, the gaze duration on other objects in both the visual low (Fig. 2, $d = 1.32$, $p = 0.049$) and visual high ($d = 2.08$, $p < 0.001$) condition were significantly longer relative to the baseline.

The auditory high condition only resulted in significantly higher scores in the NASA-TLX w.r.t. baseline (Fig. 2, $d = 1.07$, $p < 0.001$), while the auditory low did not result in any significant differences w.r.t. baseline.

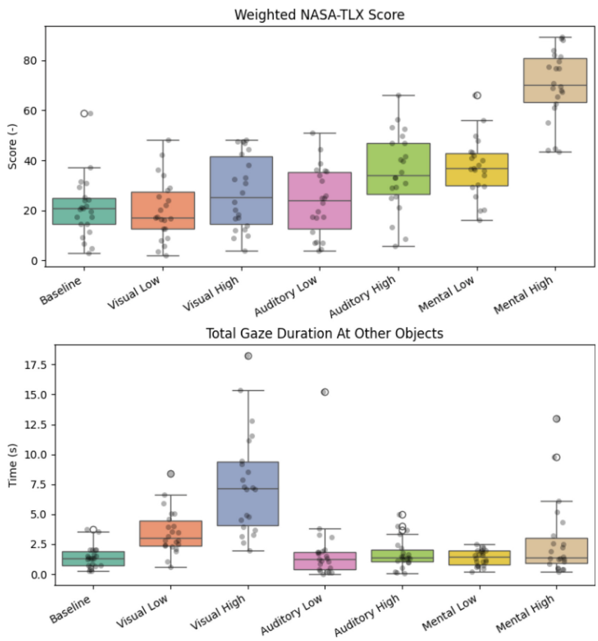

Fig. 2. Boxplots of NASA-TLX score on a scale from 0 (low cognitive load) to 100, and gaze duration on *Other Objects* across conditions.

4 Discussion and Conclusion

We ran a preliminary experiment with healthy participants who performed a virtual shopping task in immersive VR under different levels of visual and auditory stimuli and mental demands. We found that mental demand had the strongest impact on increasing cognitive load and hampering task performance, while visual stimuli, although having an effect on gaze behavior, did not significantly affect cognitive load or performance. Auditory stimuli showed minimal differences compared to baseline (only observed in the auditory high), indicating limited influence on cognitive load.

From the outcome metrics we employed to assess cognitive load, the performance and NASA-TLX scores seemed to be the more affected by the different levels of demands, while heart rate and heart rate variability showed no significant effects between conditions. The gaze behavior in the visual high condition suggests that participants indeed noticed the visual stimuli. While this preliminary study provides insights on designing virtual environments tailored into patients' specific cognitive needs, further research is needed in patients with cognitive deficits, as they might be more influenced by visual and auditory demands.

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