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ORIGINAL RESEARCH

Reaction time for processing visual stimulus in a computer-assisted rehabilitation environment

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ABSTRACT

Purpose: To examine the reaction time when human subjects process information presented in the visual channel under both a direct vision and a virtual rehabilitation environment when walking was performed.
Method: Visual stimulus included eight math problems displayed on the peripheral vision to seven healthy human subjects in a virtual rehabilitation training (computer-assisted rehabilitation environment (CAREN)) and a direct vision environment. Subjects were required to verbally report the results of these math calculations in a short period of time. Reaction time measured by Tobii Eye tracker and calculation accuracy were recorded and compared between the direct vision and virtual rehabilitation environment.
Results: Performance outcomes measured for both groups included reaction time, reading time, answering time and the verbal answer score. A significant difference between the groups was only found for the reaction time ($p = .004$). Participants had more difficulty recognizing the first equation of the virtual environment.
Conclusions: Participants reaction time was faster in the direct vision environment. This reaction time delay should be kept in mind when designing skill training scenarios in virtual environments. This was a pilot project to a series of studies assessing cognition ability of stroke patients who are undertaking a rehabilitation program with a virtual training environment.

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Visual reaction time; virtual reality; eye tracking; stroke rehabilitation

➤ **IMPLICATIONS FOR REHABILITATION**

- Eye tracking is a reliable tool that can be employed in rehabilitation virtual environments.
- Reaction time changes between direct vision and virtual environment.

Introduction

Virtual reality (VR) environments offer the possibility to train skills that can be transferable to the real world. These VR environments are employed in a wide array of industries for training [1–4] which include: airplane hangar inspection,[5] improve choice reaction time,[2] stroke rehabilitation [6] and driving simulation.[3] Currently, there is a very comprehensive VR environment that allows customizable training situations called the computer assisted rehabilitation environment (CAREN) of Motek Medical, Amsterdam, Netherlands. CAREN is an immersive virtual environment system that permits motion analysis for human rehabilitation and performance research.[3,4] This VR system is comprised of a three-dimensional motion capture system, a force-sensing treadmill and a large projection screen in which several simulation scenarios are synchronized with the motion of the patient.[4] It has been reported that stroke patients who completed their rehabilitation under the VR environment with the CAREN, have regained their abilities for walking.[7] They returned to their community life faster than the control patients training under the direct vision environment routine program.[7] The question remains whether the CAREN system can improve patients' ability to process visual information from the direct vision environment.

To study perception–motion integration under the VR environment, scientists started to incorporate eye tracking into the CAREN system for driving simulation training.[3] This type of incorporation makes us believe that VR environment in the CAREN system has a great potential for enhancing information processing in the visual-motor channel, which can facilitate rehabilitation to individuals with able bodies. In this study, we will further research this area by comparing information processing in the VR environment created by the CAREN to a direct vision environment when subjects are required to perform a simple mental calculation. Logistics behind this research is that, although the VR environment delivers favorable training outcomes for patients, there are some concerns of increasing mental workloads when performing a task, such as walking, in these type of environments.[8]

Although there is no strict definition for mental workload, it is understood to be the amount of mental demand engaged to perform a task under particular environmental and operational circumstances.[9] Since mental workload is a complex concept, it has different methods in which it can be assessed. Mental workload assessment may be categorized by the results of a task performance, physiological responses of the performer such as eye metrics and subjective ratings of performers like the NASA-TLX.[10]

Performance measurement is a complex task that can be developed through various methods. Human task performance follows a model in which the time required to rapidly move to a target area is a function of the ratio between the distance to and the width of the target, also known as Fitts' law.[11] Similarly, Hick's law dictates that the decision time of a human's performance rises

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logarithmically as the number of choices in the task increases.[12] Several eye metrics can be employed to obtain the information on a participant's cognitive load, level of distraction and decision making.[13,14] Some of these metrics are reaction time, fixation duration, pupil-response, saccades and smooth pursuit.[13,14] Of these metrics, reaction time is the main measure of cognitive information processing and is defined as the time of the first gaze movement upon a visual stimuli onset.[15] Subjective ratings of the performer are commonly used in areas in which complex motor tasks take place, but is also hard to separate each individual component, like in surgery.[16] Examples of surveys done for these metrics are the National Aeronautics and Space Administration Task Load Index (NASA-TXL) and the Dundee Stress State Inventory. Although these types of subjective assessments offer the benefit of giving a gestalt evaluation by the performer, these evaluations tend to be affected by the performer's working memory.[16]

The main goal of this research is to describe the eye behavior in both direct vision and immersive virtual environments and identify any differences if present. We are comparing eye reaction times between the VR and direct vision environments. Furthermore, we measured the performance of participants during identification and completion of several math equations while performing the secondary task (walking). Performance of the participants is measured in four variables: reaction time upon showing the math equation, reading time of the equation, giving the answer to the equation (answer time) and how correct was the verbal response using a scoring system. We hypothesize there will be differences in behavior between the VR and direct vision environment.

Methods

Participants

A total of seven healthy subjects (five females, two males; age: 30 ± 7 years) were recruited from the University of Alberta. They all had a normal or corrected-to-normal vision, without reporting any musculoskeletal disorders. All seven participants did not have previous knowledge of the VR system, since it was their first exposure to the CAREN system. Also, no special training was provided before performing the task. Methods used in the experiment were approved by the Health Research Ethical Board of University of Alberta. Consent was obtained from each participant before entering the study.

Apparatus

The 3D dynamic virtual environment was created by the CAREN system at the Glenrose Rehabilitation Hospital of Alberta Health Service (Figure 1, left). It includes a six-degree of freedom (DOF) motion base with integrated dual force plates, a 1 m $\times$ 2 m dual-belt instrumented treadmill mounted on the motion base, twelve-camera real-time motion capture system, 180-degree curved projection screen, surround sound system and the D-flow software package. The 2D direct vision environment was created in the Surgical Simulation Research Lab (Figure 2, left). A 17″ monitor was placed in front of the participants for showing the identical math equations used within the virtual setting with in their respective displaying order (Figure 2, right).

Eye-tracking

When performed in the VR environment, subjects were required to wear the Tobii Glasses 1 Eye Tracker (Tobii Technology); the Tobii Glasses consists of a scene camera, microphone, right eye tracking sensor and a recording assistant capturing at 30 Hz (Figure 1, right).

The eye tracker used in the controlled direct vision environment was the Tobii studio X2-60 (Figure 2), recording at 60 Hz. An external camera was used to record the participants' performance for each environment.

Task and procedure

Each participant performed the trials (3D and 2D VR) once on different days and locations. The trials on the CAREN system were performed at the Glenrose Rehabilitation Hospital for approximate 1 minute since the trial was under a self-paced walking. Then, the direct vision trial was performed at the SSRL with a duration of 64 seconds for all participants. All seven participants performed in the VR environment with CAREN system first, then they performed under the direct vision condition in the research lab.

In the VR environment with the CAREN, a city street scenario was displayed while subjects walked on the treadmill in a safe and individually-adjusted speed. After 35 m on the road, one of

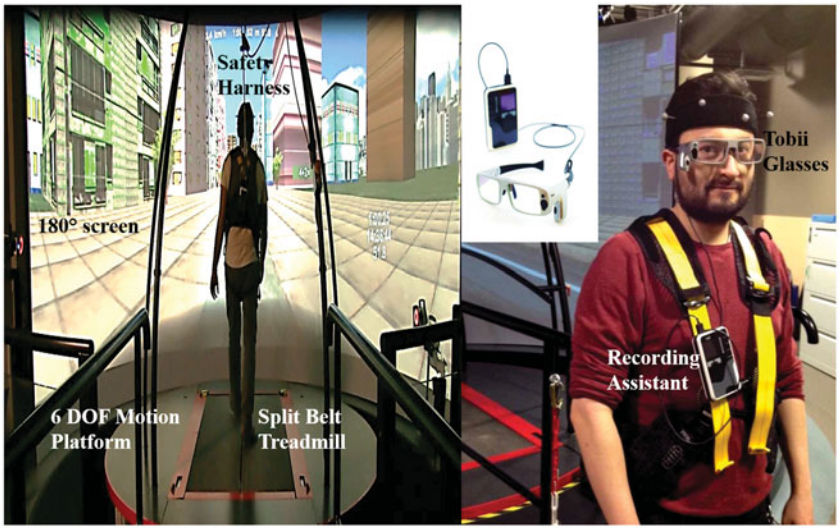

Figure 1. Virtual environment equipment. Left: CAREN system. Right: Tobii glasses 1.

eight mathematic equations was shown in a sequential order in a clockwise fashion. Each equation was displayed on the screen for four seconds. Participants were expected to read the question and speak out the answer loudly while walking on the treadmill. Audio and video recording was completed through the Tobii eye-glasses and an external digital video camera.

The same equations were displayed in the same fashion to the same group of subjects in the direct vision environment. Subjects watched the identical city-street scenario while they were sitting and watching a 17″ TV monitor. A video was playing on a desktop computer with the math equations displayed at the same on and off time as the first part of the experiment. Participants were not informed of the order in which the equations were going to show up. A head support was used with a participant-screen distance of 65 cm. Participants were asked to fix their gaze on a central point of the screen and speak out the answer loudly to the mathematical equation as soon as they could identify it. An external digital video camera was used to record the participants' verbal responses.

Measures

Four metrics were analyzed (Figure 3) in both environments: 1) Reaction time, referring to the delay of time (in milliseconds) from the moment the equation is displayed on the screen to the moment when the subject performs a fast eye movement (saccade) towards the equation. 2) Reading time refers to the time when the subject gazed on (fixation) the equation. 3) Answering time refers to the time from the moment the equation is displayed on the screen to the moment when the subject gives a verbal answer. 4) For each equation, a score was applied to measure the accuracy of the verbal answer (Table 1).

Statistical analysis

Dependent measures included reaction time, reading time, answering time and verbal answer score that were analyzed using paired *t*-test. Statistical analysis was performed using SPPSS 22.0 (SPSS Inc., Chicago, IL). Mean and standard deviations are reported for significant effects, with an *a priori a* level of 0.05.

Results

Table 2 shows the time in milliseconds (ms) of the first three variables and the verbal answer score in both environments (Direct vision and Virtual environment). A significant difference between the two environments utilizing a paired-samples *t*-test was only found for the reaction time ($t = 2.990$, $p = .004$). Specifically, the group exposed to the virtual environment required more time (mean: 524.7 ± 535.6 ms) to identify the equations in comparison to the group in the direct vision environment (mean: 295.6 ± 159.6 ms, $p = .004$). Among the participants in the CAREN, the mean reading time was 1193 ± 953 ms, which was less than the subjects of the direct visual environment but not significant (1496 ± 1107 ms, $p = .130$). The answer time between both groups did not have a significant difference. Lastly, the verbal answer score obtained for the subjects in the direct vision environment

Table 1. Verbal answer score.

Score	Feature
0	Do not recognize the equation (no saccade to equation is recorded)
1	Recognize the equation but do not give an answer
2	Recognize the equation and give a wrong answer
3	Recognize the equation and give the correct answer

Figure 2. Direct vision environment equipment. Left: Eye tracker Tobii X2-60. Right: The mathematical equations of the task.

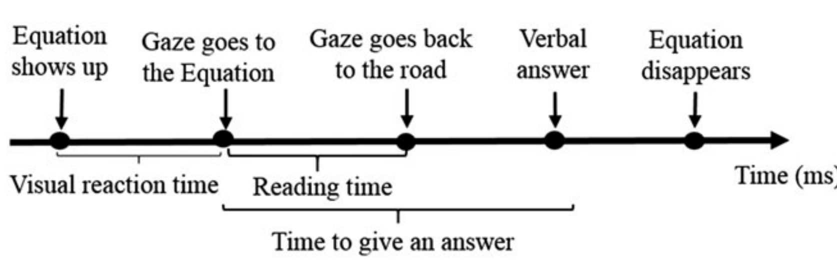

Figure 3. Metrics timeline.

Table 2. Mean and standard deviation of the performance metrics for the two environments.

Metric	Virtual environment	Direct vision environment	*p* Values
Reaction time (ms)	524.7 ± 535.6	295.6 ± 159.6	.004
Reading time (ms)	1193.2 ± 953.6	1486.1 ± 1107.4	.130
Answer time (ms)	1327.1 ± 575.6	1214.8 ± 367.4	.136
Score	2.86 ± 0.61	3.0 ± 0	.088

was 100% accurate. The virtual environment group failed 95.3% of the time to give an answer during first equation ($p = .088$).

Discussion

Our research hypothesis was supported by our results; subjects were slower to react in a virtual environment but their performance in reading and giving the answer was similar in both direct vision and virtual environments. Although there are plenty of studies on eye tracking in direct vision environments, research comparing eye behavior in direct vision and immersive virtual environments has been limited, and to the best of our knowledge, our study is the first one looking into this directly.[5,13]Our results are congruent with previous research in VR environments and cognition that show no delays in performance.[17,18] Moreover, the effect of Hick's law on performance can be seen in our experiment, as the performer was exposed to mathematical equations that could come up in any location of the screen.

Several reasons may cause longer reaction times in the virtual environment. We believe the main reason is that the participants were walking on the CAREN at the time of the task. At the beginning of the task, walking took priority over all other tasks. Once new stimuli were input, reaction to the math equations took priority and walking was displaced to a secondary level of attention. This is congruent with the hierarchical control theory of task priority displacement in virtual environments.[19] Another reason may be that this being the first encounter with a virtual environment for the participants, they did not feel the visual stimuli coming from the screen as genuine.

Typically, bottom-up cues from the environment create a perception mainly coming from a visual scene, whereas top-down cues are goal-driven and determined by cognition like knowledge and current goals.[20] In natural situations, bottom-up processing is a fast reaction. However, we believe this reaction could be delayed in virtual environments when participants are exposed to it for the first time, especially during a dual-task performance like equation identification while walking. When individuals are exposed to a new environment they focus their attention on articles to guide the gait.[21] During the trial in the CAREN, subjects addressed their gaze towards the central portion of the road for navigation purposes or to their feet in order to keep them on the treadmill. This walking task required most of the participants' attention decreasing their awareness (monitoring) of a new event, which decreased their reaction time when a cognitive task was added (equations).

There are several limitations to this study. For one, we used two different types of eye tracking devices. We plan to study eye-tracking behavior in virtual environments with a more sensible eye tracker. Second, our sample size was small. It would be beneficial to observe if eye behavior changes remain in larger groups. Lastly, we did not perform a subjective rating measurement as we were looking at objective ways to measure performance. Subjective performance could be added to future studies.

Conclusions

In conclusion, the participants took more time to react to the virtual environment stimuli as opposed to the direct vision environment but compensated without compromising their final performance. The other metrics of cognition were similar for both environments.

This was a pilot project to a series of studies for assessing cognition ability of stroke patients who are undertaking rehabilitation program with a virtual training environment. Future work should focus on applying the similar protocol to stroke patients. Methodologically, we plan to integrate subjective rating of performance to contrast them with eye tracking in different and more complex training tasks. Eye tracking has the potential to be utilized as an objective mental workload performance assessment tool in virtual environments.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Disclosure statement

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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