VIRTUAL REALITY FLIGHT ENVIRONMENTS MAY TAX WORKING MEMORY AND DISRUPT PROSPECTIVE MEMORY

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While vivid virtual reality (VR) environments may afford better performance for some flight tasks, it is possible that enhanced stimuli could overload some cognitive resources. Prospective memory (PM) is a cognitive factor sensitive to working memory and visual processing demands, and it may be a performance factor either adversely affected or enhanced by VR factors. Forty-seven pilots flew a VR flight simulation scenario, which included an auditory cue-based PM task. Self-ratings of psychological experiences in VR revealed three factors with relationships to PM: fluency, presence, and interactivity. Path analyses examined the relation of each of these factors with PM, and with two types of working memory, based on Level 1 SA. Higher fluency ratings were associated with lower PM, whereas greater presence and interactivity were correlated with better PM. Working memory also significantly mediated the effects of fluency on PM.

The use of virtual reality (VR) simulators for flight training is becoming increasingly more widespread. Moreover, VR can support a wide range of training paradigms involving many different aircraft types and flight conditions. However, there is a lack of research concerning the impact of users' psychological experiences in VR on fundamental cognitive processes during flight. The present research considered three aspects of users' psychological experiences in VR and how they might impact prospective memory (PM), which is the ability to recall or perform an intended thought or action at a future point in time (Brandimonte, Einstein, & McDaniel, 1996). PM is also a key index of pilot performance. The three VR factors were presence, interactivity, and fluency. Presence was defined as the subjective experience of "being there" in a virtual environment (Witmer & Singer, 1998), interactivity concerned the degree to which users felt that they were able to influence the content of the virtual world (Steur, 1992), while fluency reflects a form of immersion characterized by intense focus and concentration (Rheinberg, Engeser, & Vollmeyer, 2003).

PM is a cognitive factor sensitive to ongoing working memory and visual processing demands; it is also influenced by the salience of memory cues, ongoing task workload, and individual differences, such as age, cognitive health, and expertise. Van Benthem, Herdman, Tolton, and LeFevre (2015) found that in naturalistic settings, older pilots with lower cognitive health demonstrated poor PM when ongoing task workload was high, and when cue-salience was low. These results suggest that flight environments with high working memory demands impede detection of low-salience cues that are less associated with the PM task. Therefore, working memory overload may occur in visually-rich VR environments, resulting in reduced PM performance, particularly when the task is linked to low-salience PM cues. For example, Bailey, Bailenson, Won, Flora, and Armel (2012) found there to be a significant negative association between participants' levels of perceived VR presence and memory performance on a cued recall task. In this paper, path analyses with latent factors were used to examine the effects of three VR factors on PM and determine whether some of these effects were mediated by working memory.

Method

All testing took place at the Advanced Cognitive Engineering Laboratory (ACE) at Carleton University as part of a larger research agenda investigating the effectiveness of a VR-based cognitive assessment in predicting pilot risk in general aviation.

Participants

Data were collected from a total of 47 participants. Eligibility criteria for participation in the study included individuals who were in possession of a valid pilot's license and medical certificate, and who had flown as pilot in command within the past two years. The majority of participants were recruited through flyers circulated at Ottawa-region flight clubs in Ontario, Canada. Some pilots were also former participants of ACE lab aviation studies who had consented to joining a research mailing list. Table 1 provides a snapshot of pilot demographics.

Table 1. Description of Pilot Sample

	Age	License/Rating	Total Hours Flown	Total Years Licensed
Mean	47.13	4.09	1384.85	14.77
Standard Deviation	17.42	1.38	2684.51	14.34
Minimum	17	1	2	1
Maximum	71	6	12000	70

Notes. License/Rating was based on a six-point scale, where 1 = student permit, 2 = recreational permit 3= visual flight rules (no additional ratings), 4 = visual flight rules with additional ratings, and 5 = instrument rated, commercial, and instructors, 6 = airline transport.

VR Simulated Flight Apparatus

Participants wore a Microsoft Oculus Rift VR headset, which displays graphics for a 360-degree external environment and full Cessna 172 cockpit and fuselage. The virtual environment was rendered using Lockheed Martin's Prepar3D software. A prototype flight control unit was developed in-house to accompanying the functionality in the virtual cockpit. The location of the simulator controls mirrored the location of controls present in the simulated cockpit.

Flight exercise

Prior to the experimental exercise, participants were given the opportunity to practice flying in the VR simulator without additional task requirements. The virtual airfield was uncontrolled, and participants could not see or interact with the aircraft they heard information about. Following the practice exercise, participants were briefed with the details of general flight plan and notified that they would be given specific directions pertaining to airspeed, heading, and altitude over the duration of the VFR flight. Participants read-back instructions to ensure that they understood the trajectory. Participants flew in the simulator for approximately 35-45 minutes, completing a 4-leg flight with an arrival and departure at the same airport.

Measures

Auditory PM task. The PM task involved detecting the presence of an auditory cue (a spoken word) placed randomly within the pre-recorded radio calls. The radio calls were played over the headset throughout the flight, and conveyed information regarding the identity and behavior of neighboring aircraft. Participants were asked to listen to the content of the calls, and to press a button on the left side of the yoke whenever they heard the word "traffic" (the special cue). The cue word was presented randomly in approximately half of all calls. Radio calls were administered in the same order and at approximately the same time points for all participants.

Working memory. Working memory indices were developed from Level 1 SA measures (information detection) using a system similar to Endsley's (1988) Situation Awareness Global Assessment Technique (SAGAT). This method was selected, as it produced ecologically valid working memory measures, and because working memory plays an essential role in facilitating Level 1 SA. Via working memory processes, individuals are able to store and manipulate a finite quantity of information on a temporary basis (Baddeley & Hitch, 1974). New information is continuously combined with existing content in working memory to generate updated snapshots of one's environment (Endsley & Jones, 2012). To collect our working memory data, the experimental exercise was paused at random intervals, during which time the external environment and gauges were occluded, and the assessment was administered. Participants were given a set of 24 queries pertaining to situation awareness, which were divided across three freezes. While all three levels of situation awareness were queried in this experiment, only Level 1 SA items were used to index working memory for this analysis. For example, for Level I SA, a participant might be asked about details of circuit traffic, such as "State the orbit altitude of Gulf Hotel India". All participants received queries in the same order and experienced SA freezes at approximately the same time points. Each item was scored for accuracy and completeness (e.g., fully incorrect, partially correct, or fully correct). Factor analysis was conducted using only the Level 1 SA queries with strong working memory components. Two variables emerged: one latent factor involving visual updating of information from cockpit gauges (our *visual working memory* variable), and one single-item factor involving auditory updating of environmental information (wind speed and direction communicated via a ground services radio call) (our *auditory working memory* variable).

VR experiences questionnaire. Following the flight exercise, participants were asked to complete a questionnaire, which contained 14 items pertaining to user perceptual exercises in VR environments. These items (Table 2) were adapted from a questionnaire created by Mütterlein (2018), which tests perceptual experiences in VR for fluency, presence, and interactivity. All VR experience items were answered using a seven-point rating scale. Latent variables were developed from the VR experiences questionnaire items. Support was found for the three proposed constructs of fluency, presence, and interactivity. During the latent measurement model fitting, indicators were omitted from the final analysis if they resulted in factor loadings below .60, or if they brought down the value of the average variance extracted (AVE) and the composite reliability (CR) coefficients when included. Each of the final three factors demonstrated appropriate levels of internal consistency, resulting in composite reliability coefficients above the conservative threshold level of .70 (Kock, 2018). Moreover, all factors exceeded the threshold AVE value of .50 (Kock, 2018). Table 2 shows the factor loadings, cross-loadings, and final quality scores for the three VR perceptual experience factors.

Table 2. Factor loadings and quality scores for final VR perceptual experience variables

Item	Fluency	Presence	Interactivity
The Oculus Rift created a new world for me, and this new world suddenly disappeared when the exercise ended.	.25	**.86**	.31
When I removed the Oculus Rift, I felt as if I returned to the "real world" after a journey.	.21	**.83**	.33
I forgot about my immediate surroundings when I was using the Oculus Rift.	.17	**.72**	.54
I had no difficulty concentrating.	**.81**	.34	.29
My mind was free to focus on flying.	**.88**	.11	.30
My thoughts and movements felt effortless.	**.83**	.22	.37
I was totally absorbed in what I was doing.	.44	.38	**.84**
The Oculus Rift content allowed me to interact with the virtual world.	.14	.40	**.85**
I had the feeling that I could influence the virtual world of the Oculus Rift.	.39	.47	**.86**
Composite reliability	.88	.84	.89
Average variance extracted	.70	.64	.72

Note. Bolded factor loadings were the final items used in each latent VR construct.

Results

Partial least squares path analyses were conducted using WarpPLS v. 6.0, which quantified the direct effects of VR factor and working memory on PM, as well as the indirect effects of VR factors on PM, mediated by working memory. Six path models were tested: three with simple direct effects from each VR and working memory factor on PM, and three where working memory served as a mediator for effects from the VR factors on PM. Figure 1 shows a potential path model where visual working memory is mediating the effects of fluency on PM.

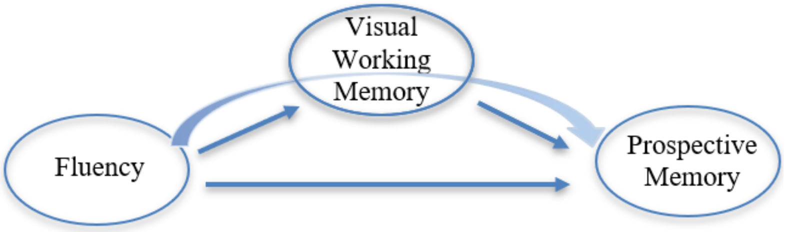

Figure 1. The straight arrows indicate direct effects, and the curved arrow indicates an indirect effect of fluency on PM mediated by visual working memory.

Fluency, PM, and Working Memory

Higher ratings for fluency were associated with lower PM, *beta*= -.28, $p < .05$ and lower visual working memory, *beta*= -.43, $p < .01$. Visual working memory was positively correlated with PM, *beta*=.35, *p* < .01. In contrast, fluency was positively correlated with auditory working memory, which itself was negatively correlated with PM, *beta*= -.28, *p* < .01. The mediation models found that significant effects of fluency on PM were mediated by both visual working memory, *beta* = -.15, *p* = .043, and by auditory working memory, *beta* = -.12, *p*=.04.

Presence, PM, Working Memory

Higher ratings for presence were associated with higher ratings for PM, *beta*= .36, *p* < .01, visual working memory, *beta*= .28, p < .01, and auditory working memory, *beta*= .25, *p* < .01. In the presence model, auditory working memory was negatively correlated with PM, *beta*= -.33, *p* < .01, and there was no significant correlation between visual working memory and PM. No mediating effects of either working memory measure were observed for the relation of presence to PM.

Interactivity, PM, and Working Memory

Similar to presence, higher ratings for interactivity were associated with higher ratings for PM, *beta*= .19, *p* = .03, visual working memory, *beta*= .29, p < .01, and auditory working memory, *beta*= .24, *p* < .01. As in the previous models, auditory working memory was negatively correlated with PM in the interactivity model, *beta*= -.35, *p* < .01, while visual working memory was positively correlated with PM, *beta*= .38, *p* < .01. No mediating effects of either working memory measure were observed for the relation of interactivity to PM.

Discussion and Implications

Our findings suggest a relationship between fluency and PM, which might be explained by working memory limitations. Fluency negatively influenced PM and visual working memory, but positively influenced the working memory variable associated with details of the virtual environment. In both cases, working memory indices were shown to mediate a significant portion of the relationship between fluency and PM, with the strongest effect being produced by visual working memory. These results suggest that experiences of fluency or intense concentration in VR significantly tap into working memory resources. Content belonging to the VR environment may engage fluency, which could in turn divert attention otherwise needed for PM. These findings are aligned with research by Bailey et al. (2012), which suggests that highly vivid sensory experiences in VR create a strain on cognitive resources.

Presence and interactivity were shown to positively influence PM and working memory. Presence, in particular, had a strong positive effect on both cognitive processes. He, Zhu, Perlin, and Ma (2018) found that VR environments with high representational fidelity support enhanced situation awareness, proposing that vivid design facilitates continuity in presence through enhancing the “realism” and “believability” of the experience. These attributes in turn help to avoid breaks in presence that interfere with a user’s awareness. Returning to working memory, enhanced engagement of presence and interactivity do not appear to create a strong demand on the cognitive resources required for PM and working memory processes. Stable and continuous experiences of these VR factors may help to mitigate situations where disconnection between a user’s virtual and external environment create competing stimuli and added attentional demands.

Future research in this area might seek to identify a core set of criteria related to vividness in flight simulators and explore the impact on VR perceptual factors. Additional work should also be done to provide validation for the proposed VR constructs, especially fluency. In order to create more robust VR cognitive training resources for pilots, researchers should seek to develop a more precise understanding of the threshold levels at which VR factors begin to support or detract from cognitive processing.

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