Auditory Presentation of Stimuli for Cognitive Load Dual Tasks in Redirected Walking

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Abstract

As more studies on redirected walking (RDW) in virtual reality (VR) arise, the importance of measuring its impact on cognitive load increases. An examination of existing publications reveals that the stimulus for the cognitive task was always displayed visually. Those existing implementations are prone to issues if used in richer virtual environments (VE) than studies until now used. Instead, an auditory presentation is proposed. We present an analysis of existing research on working memory tasks in RDW, indicating the feasibility of auditory presentation for verbal working memory paradigms.

Introduction

Using real walking as locomotion technique in virtual reality provides a realistic and well-tolerated experience as the proprioceptive and vestibular senses match the visually perceived optical flow caused by moving through a virtual environment (Razzaque et al., 2025). However, this approach limits the VE to the size of the physically available space. Redirected walking (RDW) methods allow to influence the users traversed path and thus create a seemingly bigger space (Razzaque et al., 2025). The factor by which the user's trajectory is altered is called gain. The commonly used gain is just below the perceivable threshold. Without the gain being consciously disruptive to the user the question arises, what the unconscious impact of RDW on the human cognition is.

It has been shown, that cognitive load influences gait in reality (Ebersbach et al., 2025; Nadkami et al., 2010) as well as in VR (Kannabe et al., 2014). Additional cognitive load can be created using the dual task paradigm (Woollacott& Shumway-Cook, 2002) where a concurrent secondary task is added to the walking task. This secondary task is often chosen to be taxing for working memory (WM).

Kourtesis et al. compared established tasks for WM assessment (Digit Span Task, Corsi Block Task, and Deary-Liewald Reaction Time Task) on desktop PC with VR. The results showed convergent validity and they concluded that the assessments in VR replicates the established cognitive measurements (Kourtesis et al., 2025).

In the following section an overview of studies investigating walking in VEs with working memory dual tasks is given. Then auditory stimulus presentation is proposed for studies employing RDW as a response to limitations of visual presentation.

Related work

Overall, few studies have been published on the cognitive impact of walking in VEs or the assessment of said impact with WM tasks so far.

In a CAVE VE Marsh et al. compared the impact of different locomotion techniques by administering a WM dual task. Participants had to remember and recall a sequence of either spatial (patterns) or verbal (random sequence of numbers). They found that locomotion techniques use spatial memory and thus compete with a concurrent spatial tasks (Marsh et al., 2012). To a similar conclusion came Janeh et al. when they studied the effect of cognitive load on velocity over an extended period of walking comparing walking with and without VR (Janeh et al., 2019). As dual task they utilized an auditory two-back (letter) task, thus impacting verbal WM. They recorded a significant decrease in velocity in reality as well as in VR while performing the dual task. Despite comparable results during the dual task, Janeh et al. noted a significant velocity decrease in VR conditions compared to reality, which they interpreted as cognitive demand of the task competing for resources with the increased cognitive load of the locomotion in the VE (Janeh et al., 2019).

Bruder et al. found that RDW significantly impacted verbal and spatial working memory thus requiring cognitive resources. Analysing gait during a dual task they found that the cognitive task had a significant effect on walking behaviour. They noted that participants made significantly more errors in the spatial task compared to the verbal task (Bruder et al., 2015). While Lai & McMahan compared three walking techniques for consumer VR applications they evaluated whether a verbal and spatial two-back task should be used as dual task(Lai & McMahan, 2020). The decided to use the verbal task, because they found the spatial stimuli too challenging in combination with their steering techniques (Lai & McMahan, 2020).

Nguyen et al. employed a dual task of serial seven subtraction. They determined that cognitive load had a significant impact on curvature redirection detection thresholds and participants could use higher gains without noticed during the task (Nguyen et al., 2020). Also studying redirection detection thresholds but using a different cognitive task Mostajeran et al. employed a dual-task spatial WM task while walking with different gains aiming to determine detection thresholds (Mostajeran et al., 2024).

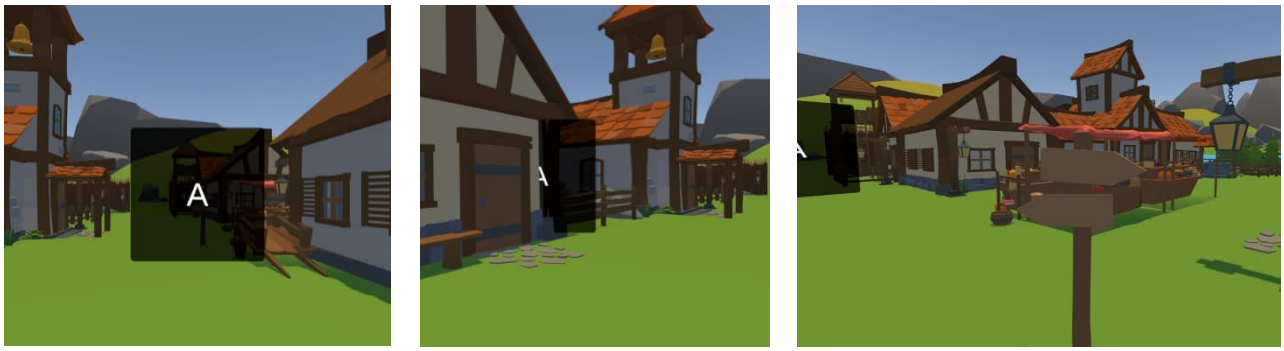
Table P 13. Studies with working memory tasks in VEs.

Paper	Cognitive (WM) task	Stimulus presented
Marsh et al, 2012	Digit span (3-5), Spatial span (3-5)	Visually
Bruder et al, 2015	Verbal 2-back, Spatial 2-back	Visually
Janeh et al, 2019	Verbal 2-back	Auditory
Nguyen et al, 2020	Serial 7-subtraction	n/a
Lai & McMahan, 2020	Verbal 2-back	Visually
Mostajeran et al, 2024	Spatial 2-back	Visually

Findings

Visual stimulus usually takes the form of a UI element with the stimulus symbol or letter. For non-VR scenarios this is displayed on the screen (Kourtesis et al., 2025; Hilbert et al., 2015) while in VR it is often displayed ahead of the user roughly at head height (Figure P 47a) (Bruder et al., 2015; Lai & MaMahan, 2020; Mostajeran et al., 2024). While the procedure is not detailed in the descriptions, it can be assumed from the depictions that the stimulus UI is placed ahead at a fixed location in the VE.

In these scenarios participants followed a straightforward path in very open and visually sparse environments that gave little incentive to look around. Although this matches the typical scenario used in RDW threshold detection, following a single straight path is a rather artificial and limited use case. However, this approach can encounter issues if the VE becomes more narrow or visually busy which will happen for scenarios that are closer to potential applications of RWD. For example, if the stimulus is placed in a fixed location in the VE, curving paths, corners, or junctions where the user may choose between multiple routes can cause problems for the placement of the stimulus (Figure P 47). Placing the stimulus closer to the participant can solve the problem for certain environments but cannot solve the problem of the user looking around and potentially missing one of the stimuli (Figure P 47c).



(a) (b) (c)

Figure P 47. Demonstration of issues with visually presented cognitive stimulus in VE as commonly used (a) stimulus obstructing scene (b) stimulus partially occluded by scene objects (c) stimulus partially out of view

Additionally, if placed naïvely the stimulus can intersect with the VE as depicted in Figure P 47b. While this could be solved with a shader, that renders the stimulus over the VE, this introduces contradicting depth cues since the stimulus is occluding closer geometry.

Therefore, we propose to use WM tasks with auditory presentation instead of visual stimuli. This could be particularly feasible for verbal n-back, serial 7-subtraction, and digit span (forward and backward) task as those need a small set of stimuli to implement.

The results of multiple unconnected studies give a first indication to the validity of the proposed solution. One study investigated auditory versus visual presented stimuli in WM assessment using Digit Span Backwards (DSB). Nakagawa et al. found indications that the user preferred cognitive strategy is more impactful than the presentation mode (Hilbert et al., 2015).

N-back is a commonly used cognitive task in VR studies as evident in Table P 13. In a study comparing the n-back performance of visual versus auditory performance, Amon & Bertenthal found that participants responded more accurately but slower for auditory presented stimulus than to the visual stimuli. They suggest that auditory stimulus creates more cognitive load than visual and conclude that stimulus modality influences encoding and cognitive processing on WM tasks. However, the performance advantage afforded by the auditory presentation was less pronounced with more difficult

n-back tasks and they noted the tentativeness of this result because the advantage was not significant when analysed with a d' signal detection measure (Amn & Bertenthal, 2018).

One drawback of the proposed solution is that for spatial WM task, which have also been used in RDW studies (see Table P 13), there is no simple conversion to auditory. However, a study comparing gait changes between a working memory dual task and a spatial attention dual task rendered no significant difference and could thus imply that changes in gait are impacted by the sharing of attentional resources rather than the cognitive mode of gait interference (Nadkami et al., 2010). This suggests that verbal instead of spatial WM assessment tasks, which can be implemented auditory, could be used in RDW studies.

Discussion

While it might be suited to visually present stimulus to create cognitive load while testing for RDW detection thresholds or environments with mainly straight paths, it seems prone to issues if used in VE with variable paths. The proposed solution of presenting auditory stimuli would eliminate these issues for verbal WM task. The results of multiple studies on WM support the feasibility of the proposed auditory presentation with verbal working memory paradigms.

Additionally, we see the concurrent processing of auditory stimulus as relevant and realistic for practical use cases such as training where information should be retained.

Future work

The authors will continue by investigating the cognitive impact of redirected walking (and other locomotion techniques) in a maze where an auditory working memory task will be administered. Additional research is needed to further evaluate scenario-independent assessment implementations for redirected walking.

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