Exploring Spatial Cognitive Residue and Methods to Clear Users' Minds When Transitioning Between Virtual Environments

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ABSTRACT

In most cases, retaining memories of things we have experienced in the past is desirable, but in some cases, we want to clear our minds so that we may focus completely on subsequent activities. When someone switches from one task to another, they commonly incur some "cognitive residue" where some of their cognitive resources such as working memory and attention remain devoted to their previous task even after they try to switch their focus to their new task. This residue could have a negative impact on their performance in the next task, and in such circumstances, it is important to reduce that residue. In this paper, we explore the concept of cognitive residue in the context of switching between virtual reality (VR) environments. We conducted a human-subject experiment (N=24) with a spatial recall task to investigate how different visual transitions might reduce participants' spatial cognitive residue. In this instance, more errors on the recall task corresponds to less spatial cognitive residue. We found that transitions that lasted one minute successfully reduced spatial cognitive residue: they significantly reduced participants' abilities to recall the positions of objects in their previous VE compared to an instantaneous cut transition. Additionally, for transitions that showed a nature scene, greater head movement significantly correlated with more spatial memory errors (i.e., less spatial cognitive residue). We discuss how these findings can be applied to support users transitioning between virtual tasks and environments in VR task switching scenarios.

Index Terms: Extended reality, transitions, task switching, spatial memory, cognitive residue

1 INTRODUCTION

Interconnected electronic media devices have led to an increase in multitasking for work and socializing purposes [34]. This has affected the cognition of people who regularly use such devices — researchers have suggested that frequently switching between tasks and contexts may lead to shallower information processing and poorer executive control [10, 39]. As augmented reality (AR) and virtual reality (VR) — altogether referred to as XR — devices and their applications grow in popularity, they will be used more frequently, for longer durations, and for a wider variety of purposes. It is reasonable to expect that people will use them in ways similar to other electronic media and switch between different XR tasks and environments quickly. Each transition (and interruption) carries with it a certain cognitive cost, a "residue," associated with incomplete disengagement from the prior task [29]. It is important to understand how XR users' cognition functions when switching between XR contexts so that we may create XR interfaces and interaction techniques that support and amplify (rather than impair) users' cognition. In this paper, we present a study about how one aspect of XR users' cognition — their spatial memory of a virtual environment (VE) — is affected by different visual transitions when switching between VEs.

When switching from one task to another, a person experiences some "attention residue" wherein their performance on the second task is temporarily impaired because some of their cognitive resources are "sticking" with their first task [29]. In experiments demonstrating the existence of this phenomenon, *more accurate recall* of something from the first task after switching to the second task corresponds to a *higher degree of attention residue*. In other words, *more* cognitive resources devoted to a previous task means *less* cognitive resources available for the current task. In this study, we focus on users' "spatial cognitive residue" in XR, or how much users' spatial understanding of one VE sticks with them after they transition into an entirely new VE.

There are cases where spatial cognitive residue might be beneficial to someone; for example, when they are frequently switching between multiple spatial tasks and need to keep information from each task in mind to perform well overall. There are also cases where attention residue is not desirable; for example, when someone wants to feel fully focused on their next activity. This might be especially true for situations in which someone switches into a meeting or social task: they will want to feel fully present with the people they are currently with, not "stuck in the past" and thinking about their previous task. We are particularly interested in manipulations that help clear a user's mind when transitioning to a new environment so that they may arrive more mentally prepared or become more quickly and fully present in the new environment.

Research on interruptions and task breaks suggests that transitioning between tasks or environments presents a natural opportunity to interact with users' cognitive residue. When someone transitions between tasks, it has been theorized that they first mentally disengage from their first task and commit to memory information about what they were doing and what their goals were [57]. Then, they mentally prepare for the next task before starting it. Additionally, research has shown that taking short breaks between tasks that include viewing nature scenes or performing exercise can reduce fatigue, increase vigor, and improve task performance [3]. Because of its interaction with users' memory related to their previous and upcoming activities, we treat this transition period between tasks and environments as an opportunity to interject interfaces and interactions that help users disengage from one environment before arriving in another, which could reduce the cognitive residue of the first environment they experience.

We conducted an exploratory human-subject study to investigate how five different visual transitions might reduce users' spatial cog-

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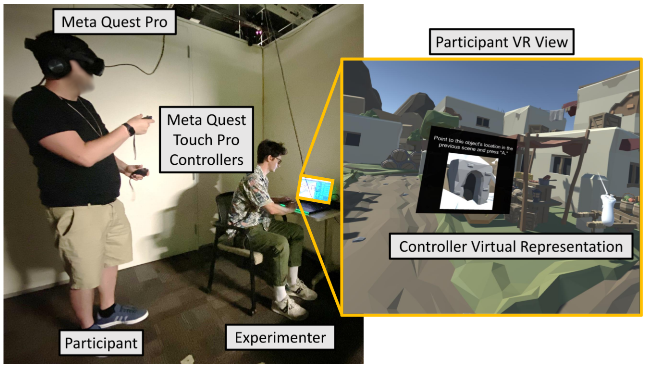


Figure 1: Annotated photo showing a participant in the experiment wearing the VR headset and holding the controller during the task. The inset shows the virtual environment from the participant's view, which the experimenter could view during the experiment.

nitive residue when switching between different VEs. The transitions included a baseline cut, fade-to-black, and a fade to an intermediate realistic nature scene. We tested two durations of the fade transitions: 20 seconds and 60 seconds. By analyzing participants' accuracy on a spatial memory task, we found that the 60-second transitions significantly *increased* participants' degrees of error on the memory task, suggesting that they *reduced* the spatial cognitive residue from the previous VE. Also, in analyzing participants' motion data during the nature scene transitions, we found that more head rotation was significantly correlated with reduced spatial cognitive residue.

2 BACKGROUND

In this section we provide the theory underlying the concept of cognitive residue. We then discuss related efforts behind mitigating problems related to it, as well as the opportunities afforded by transitions in XR experiences to do the same.

2.1 Cognitive Residue in XR

Attention residue is experienced when one's attention remains focused on a previous task even after they start working on a new task [29]. This is in contrast to cognitive closure or cognitive disengagement, when an individual cognitively "moves on," detaches, or avoids giving attention to a thought or task [13, 24, 25]. Attention residue research is also distinct from multi-tasking and task switching research, as these typically concern the time it takes to attend to a new task and complete it, regardless of any attention that may have lingered on a previous task [47]. Thus, we are concerned with the residual attention left to a prior task when a new task has begun in series (i.e., not in parallel). Furthermore, we are interested in "residues" associated with cognitive processes besides attention, especially working memory and its subordinate spatial working memory [6] which are closely related to, and overlap with, attention [5, 16]. In this work we refer to this expanded consideration of attention residue as "cognitive residue." Examples of other concepts related to cognitive residue include cognitive fixation, where individuals fixate on a concept associated with a prior exposure and fail to identify creative solutions, even if the correct solution is simpler and more obvious than the prior [35]. Another is prospective memory, where individuals remember an intention for a future action, ostensibly while conducting some other task [36].

In related work in XR, studies demonstrated that item recall performance is worse when changing between virtual and real environments [26]. Shin et al. demonstrated the complementary effect, where recall performance is better when the virtual retrieval environment matches the original virtual learning environment [50]. Other work showed that different virtual experiences could impact altruistic behaviors after the virtual experience ended [46].

In the above works, cognitive residue from VE experiences enables positive outcomes. There are many circumstances, however, where it is beneficial to reduce cognitive residue. For instance, cognitive residue is associated with decreased cognitive task performance after a task transition [31]. In these contexts, cognitive residue is considered a cost of switching between one task to another [32]. Such costs result in lower *quality* of attention, regardless of the *quantity* of attention spent on the new task [59]. In scientific research, counterbalancing or randomizing conditions to mitigate carryover order effects is an example of a strategy to mitigate cogntive residue, as experience in a prior environment or task affects our performance in the subsequent one. Thus, in this study, we are interested not only in the effects of cognitive residue, but also in the ways by which we may mitigate or reduce it.

2.2 Strategies for Reducing Cognitive Residue

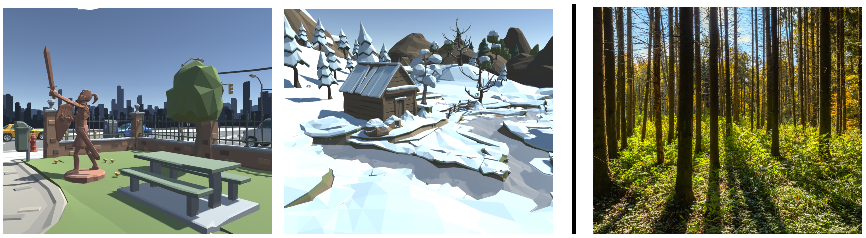
Prior work on attention residue draws connections to concepts of attention control and cognitive disengagement [30]. It would then be reasonable to expect that reducing cognitive residue could be accomplished through means that encourage cognitively disengaging from past events. Watson et al. [60] demonstrated that methods for capturing attention towards a future task can actually harm performance in an ongoing task by inducing attentional disengagement from the ongoing task, an effect similar to what would be expected from reduced cognitive residue. The literature also turns to limited attentional resource theory to explain why attention paid to one task may reduce performance on another task, i.e. there are reduced attentional resources that can be dedicated to the latter task, leading to reduced performance [4]. Albulescu et al.'s review aimed at methods for reducing accumulated strain reported that micro-breaks (breaks under 10 minutes of duration) can reduce fatigue, increase vigor, and improve task performance [3]. Similar work on using micro-breaks and nature scenery has gained traction, including attention restoration theory that predicts exposure to natural environments can improve cognitive performance by restoring attentional resources [55]. Such interventions as short as 40 seconds have been shown to be effective in improving cognitive task performance [28]. Finstad et al. ran and replicated an experiment demonstrating that 10-second micro-breaks significantly reduced performance of a memory task conducted during a concurrent judgment task [15].

While these related studies have demonstrated our goal of reducing cognitive residue between tasks outside of XR, we focus on understanding how the mind-clearing benefits of brief breaks with nature content apply in terms of XR users' *spatial* cognition.

2.3 Transitions Between XR Environments

A growing body of work has analyzed the effects of different transition techniques on XR users' experiences. These different transitions include simple ones such as instantaneous cuts and fades to black as well as more complicated ones such as geometric morphs and simultaneously displaying two overlapping environments at once [18, 21, 44, 37, 48]. For recent classifications of XR transition techniques, see [14] and [43]. The research goal in this area is often to provide a seamless user experience when transitioning users or objects from one experience or environment to another and reducing disorientation [12, 19, 23, 58]. One method commonly employed to transition users between the real world and a VE is by first displaying a virtual replica of the real world space [23, 44, 54, 58]. Such replica-based transitions have been shown to increase participants' attention to the VE [58], movement confidence [58], presence [54], virtual body ownership [22], and spatial orientation [44]. The reported durations of tested transition times are often between 1.3 and 15 seconds (e.g., [14, 20, 21, 44]). On the longer end

(a) Amusement Park (b) City Block (c) Forest Campsite (d) Medieval Marketplace



(e) City Park (f) Snowy Landscape (g) (Transition Image) Forest

Figure 2: Experiment virtual environments (VEs). (a-f) Screenshots of VEs used in our experiment, and (g) screenshot of 360° image used during Nature Scene transition conditions.

and designed for increased user interaction, Valkov and Flagge [58] used 30-second transitions. Studies have shown that users tend to prefer quicker transitions in task-based environments [14, 43], but that transitions with longer durations or that require more interaction can be engaging [58] or are more acceptable when used infrequently [43, 44].

Works analyzing transition effects on spatial memory demonstrate the effects of switching environments on item recall [26, 45, 50]. Specifically, Lamers and Lanen's work [26] and Shin et al.'s work [50] primarily address the role of environment in scaffolding new learning; when a user transitions to a different environment, the new environment does not afford the ability to use it to aid recall. This mechanism is contrasted with reducing cognitive residue, whereby attention restoration or disengagement processes "free up" attentional and cognitive resources for a new task. In this work we focus on using XR transitions not as a vehicle for transferring experiences between two environments, but rather as a tool in itself for mitigating the effects of cognitive residue. To this end, we present an experiment using cut and fade transitions featuring empty black or nature scenes for different durations to investigate how XR transitions can reduce cognitive residue between XR environments while maintaining a positive user experience.

3 EXPERIMENT

3.1 Participants

We recruited 28 participants from our university community. We removed 4 data sets from further analysis because we observed these participants to not follow instructions during the experiment. This resulted in a total of 24 participants (15 men, 6 women, 2 non-binary, 1 preferred not to respond; 19-44 years of age, M = 25, SD = 5.7). Our experimental procedure and recruitment of participants were approved by the institutional review board of our university under protocol number SBE-17-13446. All of the participants had normal or corrected-to-normal vision. None of the participants reported known visual or vestibular disorders, such as dyschromatopsia or a displacement of balance. 19 participants had used a VR head-worn display (HWD) before. The participants were either students or non-student members of our university, who responded to open calls for participation, and received $15 cash compensation for their participation.

3.2 Material

3.2.1 Hardware and Setup

Figure 1 shows a participant in our experiment's physical environment. We used a large open space in our laboratory dedicated for human-subjects studies. The experimenter sat at a desk off to the side and monitored the participant's activity during the experiment through a laptop. Participants used a Meta Quest Pro VR HWD, which supports a 96° diagonal field of view and a resolution of 1800×1920 per eye. The HWD was equipped with a Meta Quest Pro Light Blocker to block out outside light from leaking in around the periphery of the HWD. Participants used Meta Quest Touch Pro controllers to interact with the environment. The VR application used in the experiment was developed using Unity 2022.3.9f1. The application was run on a MSI Raider GE76 laptop with an NVIDIA RTX 3080 Ti GPU with 16 GB of GDDR6 video memory, an Intel Core i9 CPU, and 32 GB of DDR5 memory. The application consistently ran at 72 frames per second. The laptop was connected to the Meta Quest Pro HWD using a Meta Quest Link cable that was suspended above participants' heads to avoid that participants become tangled in the cable as they observe the virtual environments.

3.2.2 Virtual Environment and Objects

As shown in Figure 2 (a-f), we created 6 different VEs using freely-available assets from the Unity Asset Store[1][2]. Each VE contained 5 objects of interest that were approximately evenly spaced out around the origin point for the VE. Each object was approximately the same size in the HWD's field of view. The environments included an amusement park, a city block, a camp in a forest, a marketplace, a city park, and a snowy landscape. The order in which participants experienced the VEs was randomized. We generated text for an introductory narrative description for each VE as a whole and a description for each of the objects in the VE using ChatGPT 4.0[3]. We used Amazon Polly long-form voice[4] text-to-speech

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[1] https://assetstore.unity.com/packages/3d/environments/polygon-sampler-pack-207048

[2] https://assetstore.unity.com/packages/3d/characters/low-poly-winter-pack-78938

[3] https://openai.com/index/gpt-4-research/

[4] https://aws.amazon.com/polly/

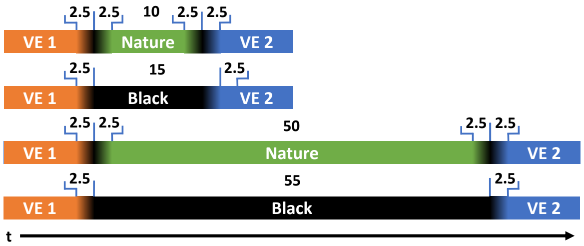


Figure 3: Timelines of the transition techniques tested. Numbers indicate the duration of each transition segment in seconds. Note that the segments representing the times when participants were in VE1 and VE2 are not to scale.

software to generate audio from the generated textual descriptions. We revised the text descriptions and re-generated the corresponding audio until all audio descriptions were approximately 19 seconds. These descriptions were played when a participant entered a given VE: first the description for the whole VE, and then descriptions for each object of interest. Each object description included instructions at the beginning directing the participant which way to turn to find the object. See Figure 7 for an example of an experimental environment's objects and Appendix A for example descriptions.

3.2.3 Visual Transitions

After the description for one of the experiment VEs concluded, 1 of 5 different visual transitions occurred that transitioned the participant's view to their next VE. We created different visual transitions based on the following factors:

- **Content (2 levels):** We tested intermediate transition content (i.e., what participants saw between VEs) that was either *Blank* (black screen, nothing displayed in HWD) or a *Nature* scene (360° image of a forest, see Figure 2 (g)).
- **Duration (2 levels):** We tested short transitions that lasted *20 seconds* total and long transitions that lasted *60 seconds* total.

We also included a separate **Baseline** condition that involved an instantaneous switch from one environment to another. Intermediate Blank transitions gradually faded the view of the VE to black, and then faded to the experiment's next VE. Intermediate Nature transitions faded the view of the VE to black, then faded into a 360° image of a forest scene, then faded to black, and finally faded to the experiment's next VE. All fading effects used a linear function to interpolate the transparency of a solid black quad placed in front of the Unity application's virtual camera over a 2.5 second period. We chose the simple cut and fade-to-black transitions because of their prevalence in other research on XR transitions (e.g., [14, 21, 37, 43]) and the simplicity for developers to implement them. We used a forest scene shown in Figure 2 (g) as an intermediate transition environment because exposure to nature images and environments has demonstrated cognitive and emotional benefits in general [38], and specifically with respect to improving performance and reducing fatigue when used as a short break between tasks [3]. The forest scene was mostly visually uniform in every direction (e.g., trees surrounded the participants with no clear differentiation between the trees that would orient participants), and we did not play audio that directed participants toward any particular direction or object in this environment. Our rationale for this transition design was for participants to experience it as a break between VEs that would not require additional cognitive resources rather than another VE that was deliberately guiding their attention. Additionally, a 360° image is not as computationally costly to render as a 3D scene, and so it could be reasonably incorporated as a loading screen for an application without too much overhead.


Point to this object's location in the previous scene and press "A."

Figure 4: Spatial memory recall task pop-up showing an image of an object the participant saw in the previous VE (i.e., before they transitioned to a new VE in which the pictured object was not present). When a pop-up appeared, participants pointed in the direction of the pictured object relative to their current location and pressed the controller's “A” button.

The 20s duration was chosen as approximately the time it takes to quit an application and load a different application on a modern consumer VR HWD. The 60s duration was chosen based on an approximate minimum recommended length for micro-breaks between tasks designed to restore cognitive resources and improve user wellbeing [3]. Visualizations of the transition timelines are shown in Figure 3.

3.2.4 Spatial Memory Recall Task

We used a pointing task to test participants' spatial memory inspired by related research measuring the accuracy of participants' spatial cognition [11, 42]. As shown in Figure 4, each spatial memory task involved showing an image to the participant of an object that was described to them in the VE they experienced before a transition (i.e., the object was not visible in their current VE). The image appeared in a world-fixed position 1.5 meters directly in front of the participant. A notification sound played when the image appeared. Then, participants pointed to where they thought the pictured object was relative to their current position and pressed the “A” button on the controller. Participants completed 5 spatial memory recall tasks in every VE: when they first arrived in a VE (i.e., right after completing a transition), after the introductory VE description, and after the first three objects were described. They did not complete spatial memory tasks in the first experimental VE because they had not yet completed a transition. The order in which the objects were tested was randomized for each environment.

3.3 Methods

For this experiment, we used a 2×2 within-subjects design with the **Duration** and **Content** transition factors, as well as an additional **Baseline** transition as described in Section 3.2.3. All 5 conditions were tested once per participant. The order of the conditions was randomized to reduce potential carryover effects.

3.3.1 Objective Data

We collected the following objective data from each participant.

- **Memory Task Accuracy:** When a participant completed each of the 5 memory pointing task trials (described in Section 3.2.4), we computed the angular difference in degrees between the forward transform of the participant's controller and the forward transform (equivalent to combining differences in azimuth and elevation) of a hypothetical controller pointed directly at the target object's position in the previous VE participants experienced. We computed the *Memory Task Error* as the mean of the angular differences for all memory trials in each condition. Smaller angular error suggests participants better remembered where the objects were in relation to their current position. In many prior works, pointing tasks are analyzed using horizontal (i.e. yaw/azimuth) angular differences, such as [33, 41]. These works test for spatial recall of inherently two-dimensional representations, such as the arrangement of objects in a maze or a 2D map. In this experiment, the objects were presented as semantically existing in three-dimensions, e.g. a plane flying through the air or a large restaurant sign mounted high on a building. We are thus interested in participants' recall of the three-dimensional locations of the objects, rather than a two-dimensional representation of space. To reinforce this, the narrative descriptions of the objects discussed in Section 3.2.2 emphasized the elevation of objects, if appropriate. Therefore, we calculate angular differences in three-dimensional space similarly to work concerned with three-dimensional pointing tasks, e.g. [53].

- **Head Rotation Data:** We logged the quaternion rotations of the VR HWD every frame during the 20s and 60s transition periods. We excluded the Baseline transition because it was instantaneous and so participants did not have time to move during it. For a given transition, we computed participants' overall head rotation based on the sum of the absolute values of the frame-by-frame angular differences (in degrees) of the VR HWD in any direction.

3.3.2 Subjective Data

While not integral to our study on the objective effects of different transitions on participants' spatial cognitive residue, we collected the following subjective data to gain a better understanding of how participants felt about the transition techniques, e.g., whether 60s would feel unbearably or unnecessarily long even if it more effectively cleared participants' minds.

- **User Experience:** We used the *User Experience Questionnaire (UEQ)* [27] to measure a participant's experience of each transition method. The UEQ consists of 26 opposing-term items on a 7-point scale with sub-scales related to the experimental condition's pragmatic qualities, and hedonic qualities, and overall attractiveness. Pragmatic qualities focus on goal-oriented aspects of design like efficiency. Hedonic qualities focus on design originality and beauty. Attractiveness refers to the overall quality of the condition in a given use case; in this experiment, the designed use case was clearing participants' minds between VEs.

- **Continuity:** We used a questionnaire on *Continuity*, or the sense of an unbroken and coherent experience, used in related studies on XR transitions [21] to capture aspects of the user experience specific to XR transitions. Each question uses a 1 to 7 scale, and the scores are combined into a mean continuity score after inverting the third question. The mean score is thus also on a scale of 1 = low sense of continuity to 7 = high sense of continuity.

- **Presence:** We used a single-item presence questionnaire developed and validated by Bouchard et al. [8] to measure the extent to which participants felt like they were actually *in* the VE on a scale from 1 = not at all to 7 = totally.

All questionnaires were administered in the experiment VR application as world-fixed user interface windows with labeled sliders that participants used their controller rays to interact with.

3.4 Procedure

After acquiring their consent to participate in the experiment, participants were briefed on the experimental tasks, experimental conditions, and VR environments. Participants then put on the VR HWD and were immersed in the VR environment. Participants followed a tutorial in VR familiarizing them with the environment and object descriptions (see Section 3.2.2), transition, and spatial memory task. Participants were allowed to ask any questions before beginning the experimental trials.

In each experimental trial, participants were immersed in a VE (see Figure 2), heard a narrative description of the VE, and directed to look at each object as described in Section 3.2.2. Starting from the second VE experienced, participants were also asked to perform the spatial memory task for objects in the prior VE during the descriptions of the objects of interest, as described in Section 3.2.4. After all objects of interest were described, participants completed the single-item Presence questionnaire using an in-situ user interface (UI) with a slider displayed on a floating window. Then, participants experienced a visual transition depending on condition, as described in Section 3.2.3. Once the last VE experience was completed, participants took off the VR HWD and sat down for a semi-structured interview on any strategies they used to complete the spatial memory tasks and what effect they felt the transitions may have had on their ability to complete the spatial memory tasks. Participants then put on the VR HWD once again and were immersed in each VE and experienced each transition again, in the same order as the experimental trials they completed. While in each VE, participants completed the UEQ and Continuity Questionnaire using in-situ UIs. During this part of the experiment narrative descriptions were not played and participants were not asked to view each object of interest or complete any more spatial memory tasks. Transitions occurred after all questionnaires for that VE were completed. After all questionnaires for all VEs were completed, participants took off the VR HWD and filled out a demographics questionnaire on a desktop computer. Finally, the $15 cash compensation was disbursed.

3.5 Hypotheses

Based on the literature about strategies for reducing cognitive residue in Section 2, we arrived at the following hypotheses regarding participants' spatial cognitive residue of their previous environment after transitioning to a next environment:

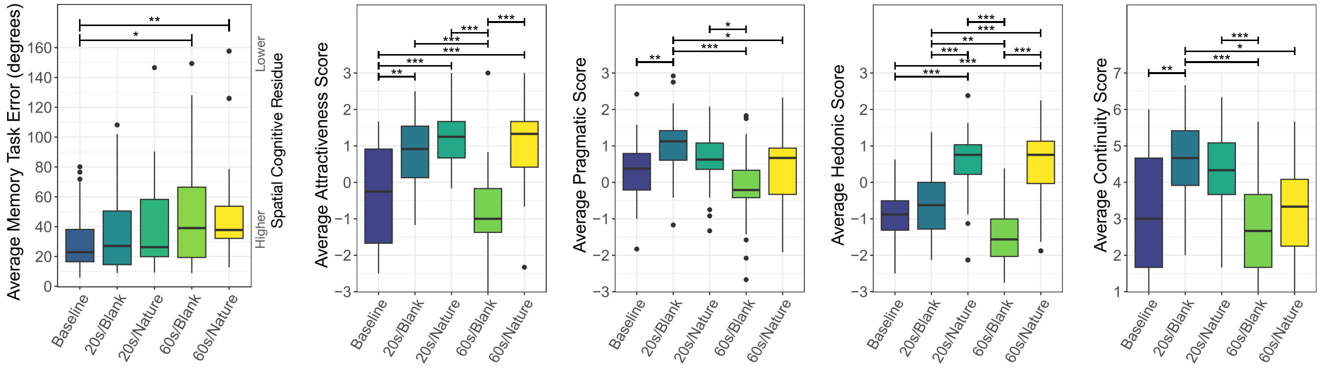
H1 60s transitions will lead to lower spatial cognitive residue than 20s transitions, which will lead to lower spatial cognitive residue than the Baseline transition.

H2 Nature scene transitions will lead to lower spatial cognitive residue of participants' first virtual environment than Blank transitions, which will lead to lower residue than the Baseline transition.

4 RESULTS

4.1 Objective Data

We performed our data analysis using R version 4.4.0 and the following packages: tidyverse, lme4, ordinal, datawizard, emmeans, ggplot2. We first analyzed the distribution of our data using Shapiro-Wilk tests, Q-Q plots and histograms. We used Generalized Linear Mixed Models (GLMMs) [17, 56] to analyze our data, which are robust to non-normally distributed data and allow for modeling the appropriate distribution of the data. Moreover, we used GLMMs to account for our within-subjects repeated measures experiment design (i.e., experimental observations nested within subjects). To optimize GLMM convergence, we normalized all of our continuous data into the range $(0, 1)$ without altering the distribution of the data using Smithson & Verkuilen's formula implemented in the datawizard R package [52].



(a) Average Memory Task Error (b) UEQ: Attractiveness (c) UEQ: Pragmatic (d) UEQ: Hedonic (e) Continuity

Figure 5: Results. (a) The average Memory Task Error (angular) for each experimental condition. Lower angular error values on the experimental spatial memory pointing task correspond to higher spatial cognitive residue as indicated by the qualitative scale on the right. (b-d) User Experience Questionnaire (UEQ). (e) Continuity questionnaire.

In general, for each measure we report on in this section, we compared different models going from the simplest form (e.g., considering only the experiment condition as fixed effect and the participants' ID as random effect) to the most complex (e.g., also considering interactions between condition and motion as both fixed effect and random effect depending on participants' ID). The factors we examined in candidate models included experiment condition, transition duration, transition content, head rotation, experiment trial number, which VE came before or after the transition, and users' subjective ratings related to the VEs and the transitions (presence, continuity, and UEQ scores). We compared the models based on their complexity and how well the data supported them using the information criteria AIC [2] and BIC [49]. The model diagnostics, including scaled residuals, for all models presented in this section indicated adequate model fit. P-values were estimated using the Satterthwaite degrees of freedom method, with p-values less than 0.05 considered statistically significant. All post-hoc pairwise comparisons used Tukey adjustments for multiple comparisons.

4.1.1 Memory Task Error

The average angular Memory Task Error is shown in Figure 5 (a). As indicated by the qualitative axis on the right in subfigure (a), there is an inverse relationship between the average angular Memory Task Error and spatial cognitive residue. To analyze the relationship between average Memory Task Error and the transition conditions, we used a Gamma distribution, as the data were right-skewed, and a log link function to fit a GLMM. Using the process described in Section 4.1, we chose a model with Condition as the only fixed effect and participants' ID (PID) as the random effect.

Analysis of deviance using Type II Wald Chi-Squared tests showed a significant effect of Condition on the average angular Memory Task Error ($\chi^2(4) = 14.01$, $\mathbf{p = 0.007}$). The fixed effects analysis revealed significant effects of Condition on average angular Memory Task Error for the intercept, representing the expected outcome of the Baseline condition (Estimate = -1.95, SE = 0.19, $\mathbf{p < 0.001}$); the 60s/Blank (Estimate = 0.57, SE = 0.21, $\mathbf{p = 0.005}$); and 60s/Nature (Estimate = 0.69, SE = 0.21, $\mathbf{p < 0.001}$) conditions. No significant effects were found for the 20s conditions (Blank and Nature). Random effects analysis indicated a variance Estimate of 0.20 (SD = 0.44) across participants. Post-hoc comparisons showed specific differences between the Baseline and 60s/Blank ($\mathbf{p < 0.05}$) conditions, as well as between the Baseline and 60s/Nature ($\mathbf{p = 0.008}$) conditions.

4.1.2 Head Rotation During Nature Scene Transitions

During the user study, we observed that participants in the Nature conditions looked around more during the transition compared to Blank transitions. This is not surprising as the Nature scene was indeed chosen to encourage this behavior. Moreover, in the interview period, 14 participants shared that they felt the Nature transitions caused them to perform worse on the spatial memory task because as they looked around and took in the forest scene, they lost track of where they were in the previous environment. Additionally, participants' UEQ scores for the 20s and 60s Nature transitions show significantly higher scores than Blank transitions of the same respective durations for the Hedonic sub-scale (which measures participants' perception of the stimulation and novelty [27] of the transition). We performed a follow-up analysis to determine whether the amount that participants looked around in the Nature transitions affected their ability to recall objects from the previous scene. We excluded the Baseline condition from this analysis because it was instantaneous and so participants had no time to look around. We excluded the Blank transitions from this analysis because there was nothing for participants to look at, and so head rotation in these cases would not be meaningfully associated with exploring or "getting lost in" the transition environment itself.

The average angular Memory Task Error data was right-skewed, so we fitted GLMMs to our data using a Gamma distribution and log link function. After evaluating several models with the process described in Section 4.1, we used a GLMM with Head Rotation as fixed effect and participants' IDs as random effects. Analysis of deviance using Type II Wald Chi-Squared tests showed a significant effect of Head Rotation on average angular Memory Task Error ($\chi^2(1) = 10.22$, $\mathbf{p = 0.001}$). Fixed effects analysis revealed significant effects for Head Rotation (Estimate = 1.08, SE = 0.34, $\mathbf{p = 0.001}$). Reversing the data scaling to fit the model described in Section 4.1, this effect Estimate means that an increase in Head Rotation by 360° corresponds to an increase of approximately 6.67° in the average angular Memory Task Error. This relationship, along with the inverse relationship with spatial cognitive residue (right axis), is shown in Figure 6.

4.2 Subjective Data

4.2.1 User Experience

The results for participants' reported UEQ scores for the different transitions are shown in Figure 5 (b-d). The UEQ provides 25 questions for 3 sub-scales to cover different dimensions of the user experience: Attractiveness, Hedonic quality, and Pragmatic quality. Participants' scores for each dimension are averaged per Condition.

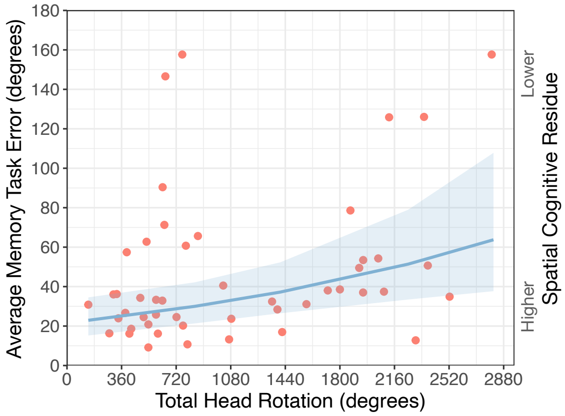


Figure 6: Scatterplot displaying the positive relationship between average angular Memory Task Error and Total Head Rotation for the Nature transitions. The blue line shows the Estimated effects of the Head Rotation predictor for the GLMM fitted to our data, with 95% confidence interval. The right axis provides a qualitative indication of the inverse relationship between the average angular Memory Task Error and spatial cognitive residue.

These data were normally distributed, so we modeled them using a linear mixed model (LMM) [17] with Condition as fixed effect and PID as random effect.

For the model fitted for Attractiveness, fixed effects analysis revealed significant effects on average Attractiveness score for the 20s/Blank transition (Estimate = 1.22, SE = 0.32, $\mathbf{p} < \mathbf{0.001}$), the 20s/Nature transition (Estimate = 1.53, SE = 0.32, $\mathbf{p} < \mathbf{0.001}$), and the 60s/Nature transition (Estimate = 1.40, SE = 0.32, $\mathbf{p} < \mathbf{0.001}$). The analysis of deviance using Type II Wald Chi-Squared tests further supported a significant effect of Condition on Attractiveness, $\chi^2(4) = 65.93, \mathbf{p} < \mathbf{0.001}$. Random effects analysis showed a variance of 0.05 (SD = 0.23) across participants. Post-hoc pairwise comparisons revealed significant differences between Baseline and 20s/Blank transitions ($\mathbf{p} = \mathbf{0.002}$), Baseline and 20s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$), Baseline and 60s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$), 20s/Blank and 60s/Blank transitions ($\mathbf{p} < \mathbf{0.001}$), 20s/Nature and 60s/Blank transitions ($\mathbf{p} < \mathbf{0.001}$), and 60s/Blank and 60s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$).

For the model fitted for Hedonic quality, fixed effects analysis revealed significant effects on average Hedonic score for the intercept which represented the expected outcome of the Baseline transition (Estimate = -0.90, SE = 0.20), the 20s/Nature transition (Estimate = 1.33, SE = 0.24, $\mathbf{p} < \mathbf{0.001}$), and the 60s/Nature transition (Estimate = 1.36, SE = 0.24, $\mathbf{p} < \mathbf{0.001}$). The analysis of deviance using Type II Wald Chi-Squared tests further supported a significant effect of Condition on Hedonic score, $\chi^2(4) = 95.14, \mathbf{p} < \mathbf{0.001}$. Random effects analysis showed a variance of 0.25 (SD = 0.50) across participants. Post-hoc pairwise comparisons revealed significant differences between Baseline and 20s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$), Baseline and 60s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$), 20s/Blank and 20s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$), 20s/Blank and 60s/Blank transitions ($\mathbf{p} = \mathbf{0.01}$), 20s/Blank and 60s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$), 20s/Nature and 60s/Blank transitions ($\mathbf{p} < \mathbf{0.001}$), and 60s/Blank and 60s/Nature transitions ($\mathbf{p} < \mathbf{0.001}$).

For the model fitted for Pragmatic quality, fixed effects analysis revealed significant effects on average Pragmatic score for the 20s/Blank transition (Estimate = 0.82, SE = 0.23, $\mathbf{p} < \mathbf{0.001}$). The analysis of deviance using Type II Wald Chi-Squared tests further supported a significant effect of Condition on Pragmatic score, $\chi^2(4) = 27.75, \mathbf{p} < \mathbf{0.001}$. Random effects analysis showed a variance of 0.27 (SD = 0.52) across participants. Post-hoc pairwise comparisons revealed significant differences between Baseline and 20s/Blank transitions ($\mathbf{p} < \mathbf{0.01}$), 20s/Blank and 60s/Blank transitions ($\mathbf{p} < \mathbf{0.001}$), 20s/Blank and 60s/Nature transitions ($\mathbf{p} = \mathbf{0.03}$), and 20s/Nature and 60s/Blank transitions ($\mathbf{p} = \mathbf{0.03}$).

4.2.2 Continuity

The results for participants' ratings of Continuity per condition are shown in Figure 5 (e). Participants' average reported Continuity scores per condition were right-skewed, so we ran a GLMM using a gamma distribution and log link function using Condition as the fixed effect and PID as the random effect to analyze the relationship between Condition and Continuity. Fixed effect analysis revealed significant effects of the intercept, which represented the expected outcome of the Baseline transition (Estimate = 1.13, SE = 0.10, $\mathbf{p} < \mathbf{0.001}$); the 20s/Blank transition (Estimate = 0.38, SE = 0.11, $\mathbf{p} < \mathbf{0.001}$); and the 20s/Nature transition (Estimate = 0.26, SD = 0.11, $\mathbf{p} = \mathbf{0.02}$). The analysis of deviance using Type II Wald Chi-Squared tests further supported a significant effect of Condition on Continuity, $\chi^2(4) = 31.41$, $\mathbf{p} < \mathbf{0.001}$. Random effect analysis showed a variance of 0.14 (SD = 0.38). Post-hoc pairwise comparisons revealed significant differences between the Baseline and 20s/Blank transitions ($\mathbf{p} = \mathbf{0.01}$), 20s/Blank and 60s/Blank transitions ($\mathbf{p} < \mathbf{0.001}$), 20s/Blank and 60s/Nature transitions ($\mathbf{p} = \mathbf{0.01}$), and 20s/Nature and 60s/Blank transitions ($\mathbf{p} < \mathbf{0.001}$).

4.2.3 Presence

Participants reported their sense of presence once for each VE on an ordinal 1-7 scale. Since this data was not averaged like the other subjective responses, it remained ordinal data. In this case, we used a cumulative link mixed model (CLMM) with a logit link function [1] to fit the presence data. We fit the CLMM to predict Presence using Condition as fixed effect and PID as random effect. Fixed effects analysis revealed no significant effects of Condition on Presence. Random effects analysis showed a variance of 4.74 (SD = 2.20) across participants.

5 DISCUSSION

5.1 Compared to an instantaneous switch, 60-second transitions correlate with less spatial cognitive residue

In this experiment, we investigated the concept of spatial cognitive residue, which refers to how much of a previous VE sticks in a user's memory even after they transition to a new VE. We are particularly interested in ways that this residue may be reduced so that the user can arrive in their next environment with less of their cognitive resources tied up in their previous activity. As described in Section 4.1.1 and shown in Figure 5 (a), our results provide evidence for the impact of transition condition on spatial cognitive residue, with 60-second transitions using fade-to-black and intermediate nature scenes leading to increased errors on spatial memory tasks compared to an instantaneous scene switch. Increased error corresponds to less spatial cognitive residue, so we conclude that the 60-second transitions effectively reduced spatial cognitive residue. However, we did not find that 60-second transitions led to increased spatial memory task errors compared to 20-second transitions, so we partially accept our hypothesis H1. This finding aligns with previous research that has demonstrated that taking microbreaks between 40 seconds and 10 minutes while working can be helpful for recovering cognitive resources and improving task performance [3]. In our case of investigating spatial cognitive in an XR context, 60 seconds was enough to reduce participants' spatial memory of their previous environment. We did not find differences based only on transition content, so we do not accept hypothesis H2. Future work could examine how other transition durations or content affects participants' cognitive residue, and how interpersonal factors or other transition modalities may affect cognitive residue.

5.2 More head motion during nature scene transitions correlates with less spatial cognitive residue

As described in Section 4.1.2, we observed that participants seemed to look around more during the transitions showing the nature scene compared to the blank transitions, and as shown in Figure 5 (d), their Hedonic UEQ scores showed that they thought of the nature scenes as more stimulating and novel than the other transitions. Therefore, we conducted a follow-up analysis that showed that increased head rotation during the nature scene transitions led to increased errors on the spatial memory task. These results provide evidence that more overall head rotation during stimulating transition periods correlates with decreased spatial cognitive residue. The takeaway from this finding is that when designing transitions to clear users' minds between VEs, drawing users' attention to different visual elements and encouraging head rotation can be helpful.

Future work could investigate the relationships between motion and spatial cognitive residue further. For instance, it would be interesting to study how different kinds and degrees of motion in participants affect spatial cognitive residue, e.g., is it possible to reduce spatial cognitive residue by inducing different head and hand movements, or by causing the user to complete more rotations in a shorter amount of time? 3 participants noted that they felt the trees in the Nature scene served as a spatial grounding point for them, which may have increased their confidence in their spatial memory task performance. A dynamic distractor without a spatial anchor point (e.g., an animated butterfly flying around, similar to work on distracting users from VE rotations in redirected walking [40]) could be employed to more fully spatially disengage users from a previous environment.

5.3 Nature scene transitions rate more highly for attractiveness and hedonic qualities

Both the 20s and 60s Nature transitions scored higher for the Hedonic sub-scale compared to the Blank transitions of the same respective duration, suggesting that participants found the nature transitions more stimulating and novel [27]. Both of these transitions were also rated higher than the Baseline and 60s/Blank transitions for the Attractiveness sub-scale, suggesting that participants perceived them as better overall at clearing their minds when transitioning between different VEs. Both the shorter Nature and Blank transitions scored significantly higher on the UEQ Pragmatic subscale than the 60s/Blank transition. This result is not surprising; it is reasonable that a minute-long transition without additional stimulation was not rated highly for questions related to efficiency and speed. The high UEQ scores for the 60s/Nature transition suggest that users tolerate the longer duration for this transition for our experimental task and context. Other XR transitions studies have found that users prefer faster transitions in continuing task-based contexts [14, 43], but our tested context is different in that it focuses on differentiating one VE from another. In this way, our findings align with previous work that found users accept longer durations or interaction when transitioning between environments infrequently or that are dissimilar [43, 44].

5.4 Perceptions of continuity and presence

For the questions related to Continuity [21], the 60s/Blank transition and the 60s/Nature transition were perceived significantly less continuous than the 20s/Blank transition. Based on the significant differences we found in spatial cognitive residue, we expected that these transitions also would be rated lower for Continuity than the Baseline simple cut transition. The questions we used are not a validated questionnaire for measuring continuity between different environments, and perhaps the development of a validated measure would be beneficial for better understanding participants' perceptions of continuity.

In our study, we found no effects of the transition conditions on participants' presence scores for each VE. In contrast to studies finding that different transitions can affect presence [22, 54], this lack of an effect was desired for our study because a different sense of presence in one VE may cause differences in memory performance related to that VE [7, 9]. Examining how different levels of presence affect cognitive residue when transitioning between XR environments is an opportunity for future work.

5.5 Limitations

One limitation of our study is that we instructed participants they would complete the spatial memory task before the experiment. This was because we used a within-subjects design and they would eventually figure out their memory would be consistently tested with these tasks. Further, we instructed participants to primarily try to enjoy whatever VE they currently found themselves in and that they should try to avoid optimizing their behavior to remember exactly where everything was in a given VE. This was an attempt to measure participants' natural spatial memory abilities based on the experimental conditions. However, it is not possible to capture this perfectly with this experimental setup. Future work could examine the effects of different transitions on spatial cognitive residue when participants do not expect to complete a memory test. Additionally, while the forest environment displayed during the Nature transitions was mostly visually uniform and did not involve guidance for users to look in certain directions, it may be interesting for future work to examine the extent to which participants experienced spatial cognitive residue of the intermediate environment. Other studies using calm environments in XR transitions (e.g., [38, 51] used 3D environments, whereas we used a static 360° image, and future work could investigate whether this affects participants' cognition. Last, our experiment also involved the participants purely taking in information about the different VEs. To get a more complete picture of how transitions affect users' cognition, future research could study cognitive residue in a task-based scenario and measure how different kinds and durations of transitions affect users' task performance.

6 CONCLUSION

In this paper, we presented a human-subject experiment (N=24) investigating how different XR transitions affect users' spatial cognitive residue after switching to new VEs in a spatial memory recall task. The transitions included an instantaneous cut, fade-to-black, and a fade to an intermediate realistic nature scene. We tested both fading transitions with 20-second and 60-second durations. Our findings show that the 60-second duration of transition significantly impacts spatial cognitive residue compared to the instantaneous cut, and that when a nature scene is used during the transition, more head rotation significantly correlates with reduced spatial cognitive residue. Based on this work, we recommend longer transition durations (i.e., 60s vs 20s or instantaneous) between experiences if reduced spatial cognitive residue is desired. Furthermore, increasing engagement in an intermediate scene can also yield reductions in spatial cognitive residue while improving subjective experience. These findings offer important design implications for supporting cognitive performance when transitioning between virtual tasks and environments in future XR task-switching contexts.

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A EXPERIMENT ENVIRONMENT EXAMPLE

(a) Signpost (b) Water Well (c) Cheese Wheel (d) Shield (e) Pumpkins

Figure 7: Example experiment environment objects. The medieval marketplace environment contained distinct virtual objects that the user was directed to look at: (a) signpost, (b) water well, (c) cheese wheel, (d) shield, and (e) group of pumpkins. These objects were placed evenly around the user so that they had to complete a full rotation when the narrative directed them to look at all objects.

For this marketplace environment, the following narrative played to direct the participants' attention to each object pictured in Figure 7 in sequence:

- **Intro**: In the town's bustling marketplace, stalls teem with various goods. The air buzzes with commerce as artisans hawk and traders barter. Each stall unfurls a tapestry of local lore, where every trinket tells the story of a thriving community. Turn until you face toward the signpost.
- **Signpost**: At the crossroads, a weathered signpost silently directs travelers. Its arrows, painted in colors once bright, now muted by time, direct a ballet of footsteps to hidden treasures, secret delights, and the pulsing heart of the marketplace's ever-unfolding story.
- **Water well**: To the right of the signpost, the town well stands in the square's sun-dappled shade. Its stone rim, worn smooth by countless hands, echoes with the gossip of generations. Drawing water from the well does not just provide a source of water to the townspeople, but also a source of neighborly connection.
- **Cheese wheel**: To the right, an enormous wheel of cheese stands as a monument to the town's culinary pride. Aged to perfection, its golden rind encases a rich history of flavors, a testament to the artisan's craft. It draws patrons like bees to honey, eager for a taste of tradition.
- **Shield**: To the right of the cheese, a shield leans against a marketplace stall, its surface a mosaic of battle stories. The shield displays a blend of valiant blues and purples to signify the bearer's courage. It's not just armor, but a legacy waiting to safeguard another through future skirmishes.
- **Pumpkins**: Last, to the right of the shield sit three pumpkins, their orange hues capturing the essence of harvest. Carved by time and nature, they are the unsung heralds of autumn's bounty in the marketplace, waiting to become pies or lanterns, the centerpiece of seasonal festivities and family feasts.
- **Outro**: Thank you for visiting this marketplace. You will soon be transitioned to the next environment.