Master Thesis Cognitive Science

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Cognitive Neuroscience

The Doorway Effect For An Object Layout Memory Task

An Examination Using Immersive Virtual Reality

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May 1, 2024

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Abstract

The “doorway effect” or location updating effect is the decrease in performance for a simple memory task after passing through a doorway. Walking through doorways, according to the Event Horizon Model, constitutes the passing of an event boundary and switching between two mental event models - thus creating an interference effect on memory items. While previous research has consistently demonstrated this effect using a simple memory task, the present study aimed to take a closer look at the robustness of this phenomenon by applying a new, more complex object layout memory task, using a highly immersive virtual reality. No convincing evidence for the presence of a location updating effect could be found, but this study still reveals potential future research opportunities. In particular, using measures of subjective confidence as well as higher working memory loads seems to be a promising direction to examine the generalizability of the “doorway effect” to different memory tasks.

Zusammenfassung

Der “doorway effect” oder “location updating effect” beschreibt, wie einfache Aufgaben für das Arbeitsgedächtnis beeinflusst werden, wenn Probanden eine Tür passieren - die Gedächtnisleistung verschlechtert sich nach dem Durchqueren einer Tür. Laut dem Event Horizon Model ist dieser Vorgang äquivalent zu dem Passieren einer Event-Grenze und damit dem Wechsel zwischen zwei mentalen Event Modelle, was einen Interferenzeffekt zur Folge hat. Die bisherige Forschung konnte diesen Effekt konsistent und wiederholt replizieren, wobei meistens dieselbe, einfach Arbeitsgedächtnis-Aufgabe genutzt wurde. Die vorliegende Studie nutzt eine immersive Virtual Reality, um die Robustheit des “doorway effects” im Kontext einer komplexeren Gedächtnis-Aufgabe (Gedächtnis zu einem Layout verschiedener Objekte) zu untersuchen. Keine überzeugenden Daten für einen solchen Effekt konnten gefunden werden. Trotzdem zeigt diese Studie Möglichkeiten für die zukünftige Forschung auf: Messungen der “confidence” bzw. subjektiven Sicherheit der Probanden sind vielversprechend, genau wie eine Untersuchung des “doorway effects” mit Aufgaben, die das Arbeitsgedächtnis in stärkerem Maße belasten. Dies alles kann helfen, die Generalisierbarkeit des Phänomens sowie seine Anwendbarkeit auf andere Gedächtnisaufgaben zu untersuchen.

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1 Introduction

During our daily life, we move through our environment without constantly thinking about it. Passing from one room into another might be one of the most insignificant actions we do day by day, but the simple act of walking through a door might influence the cognitive processing of whatever we are thinking about - even if the spatial structure of our environment is completely irrelevant to us at that time.

That our cognitive processes are influenced by the environment that we are currently in, is no surprise. In particular, while we are working on a memory task, the environment is encoded along with what we are trying to remember, even if there is no causal or semantic relationship. Godden & Baddeley (1975) showed in a now well-known experiment that word lists are better remembered if the environmental context is the same while learning and during recall - in particular, divers could recall word lists learned under water better if they were under water, and their performance decreased if they had to recall that list on dry land. This concept is also known as the encoding specificity phenomenon (Thomson & Tulving, 1970).

More recently, there are several studies that examine working memory performance while people move from one room to another. While this is not at all such a significant context change as diving under water, there is a remarkably consistent effect coined the “doorway effect”: When passing from one room to another, memory performance declines (Radvansky & Copeland, 2006).

However, even though both phenomena appear to be variants of the same encoding specificity, or context-dependent memory phenomenon, a closer inspection of the “doorway effect” leads to a different conclusion, as reinstating the original encoding context after walking through a doorway does not improve memory performance again (Radvansky et al., 2011), in contrast to the findings of Godden & Baddeley (1975).

The present study aimed to examine the “doorway effect” by trying to replicate it using a different memory task, and additionally looking at the influence that context changes have on this effect.

1.1 The "doorway effect" and event cognition

The "doorway effect" or location updating effect is currently mainly explored from an event cognition perspective - whatever happens in one room constitutes an event, and passing through a doorway means passing an event boundary.

Usually, to demonstrate that walking through doorways causes forgetting, participants are confronted with a very simple task: They are instructed to pick up an object, move through a door into another room and put the object down. Then they pick up the next object and repeat this process. However, shortly after entering the second room, a memory probe appears and participants have to respond whether the memory probe is the object they are currently carrying, the object they just put down, or a new, different object. Remarkably, memory performance as measured by response time and response correctness declines after walking through the door as compared to simply walking through a large room without a doorway - and this happens in a more pronounced way for the "associated", currently carried object (Radvansky & Copeland, 2006). This finding is impressive for several reasons: The actual memory load is very low (only the two most recently seen objects are relevant). Additionally, the spatial structure of the room and the fact that participants walk through a door or not is completely irrelevant for the memory task. Lastly, this effect has repeatedly been demonstrated by having participants experience that environment through a non-immersive virtual reality - this means that they control their movement via keyboard or controllers, and they view the environment and their interaction with the objects only on a computer screen.

Radvansky et al. (2011) demonstrated that this forgetting after walking through a doorway cannot be reversed by simply going back to the original room and thus reinstating the original context, which lead the authors to reject a context-dependent memory account of the doorway phenomenon. Rather, they argue for an event-cognition based account.

In particular in this view, each room and everything that happens in it might be classified as a single event by the brain. For example, when putting a red ball onto the table in room A and picking up a blue cube, both of these objects are now connected to the mental “event model” of room A. When entering room B through a doorway, a new event model needs to be created: This new model encompasses room B and the blue cube that is currently carried - since it now also is in this second room. Importantly, if now a recognition probe for the blue cube is presented, there is an interference happening: Both, room A and room B contain the probed-for object and thus both event models are activated. The resulting interference is assumed to be the reason why memory performance is decreased as compared to the “dissociated” red ball; if the red ball would be the memory probe, then only the event model for room A would have to be activated, with no further interference. If the doorway is removed, room A and room B are perceived as one big, combined room and thus only a single event model needs to be created.

Importantly, this account of event cognition also assumes that there is always only one current, activated event model, which usually contains the immediate and relevant surroundings - for example, the room that one is currently in. When walking through a doorway, this currently active event model switches and the object currently carried is immediately integrated into the newly activated model (Radvansky, 2012).

It is important to note that using this theoretical framework, it is easy to explain why returning to the original room after walking through a doorway does not counteract the forgetting: The carried object still is present in two different event models. The “Event Horizon Model” is a theory based on five principles (Radvansky, 2012) that is used in previous research to explain this surprisingly consistent doorway phenomenon.

With this background, doorways are often assumed to be event boundaries that separate event models, and experimental variations have repeatedly shown evidence in favour of this explanation. There has been a multitude of studies examining the “doorway effect” from different perspectives (Lawrence & Peterson, 2014; Logie & Donaldson, 2021; McFadyen et al., 2021; Pettijohn et al., 2016; Pettijohn & Radvansky, 2015, 2018; Radvansky et al., 2010, 2011; Radvansky & Copeland, 2006; Seel et al., 2018; Wang et al., 2023; Watson & Gaudl, 2021), and a few of these are especially noteworthy in the context of the present study.

Most of those studies describe the experimental task as being “virtual environments” that participants walk through and where they pass through doorways. However, these virtual environments are usually depicted only on a simple computer monitor. Participants control their movement by pressing keys or by using a controller, and even the distinction between the “associated” and “dissociated” object might be questioned, since participants do not actually “carry” the object with them, but have to imagine that they do, aided by the visual representation on the screen.

There are a few exceptions that are interesting: Lawrence & Peterson (2014) had participants memorize a real environment by having them physically walk through an actual room constellation - the argument being that participants do not physically have to pass through a doorway, since imagining oneself doing so would have the same effect on cognitive processes. In fact, this study could demonstrate the presence of a “doorway effect”. This is evidence in favour of the Event Horizon Model, since that model does not depend on the actual physical or even visual experience of passing through an event boundary, but rather is based on the mental structuring that happens.

Similarly, Pettijohn & Radvansky (2018) had one participant execute a standard version of the doorway experiment, while a second participant passively watched. Both participants were probed for memory, and both participants did exhibit a location updating effect, albeit smaller for the passive participant. Again, this provides evidence that merely the mental classification of something being an event boundary, regardless of actual personal experience, influences working memory performance.

However, while the “doorway effect” has been found in real (Radvansky et al., 2011), virtual or imagined environments, McFadyen et al. (2021) could not replicate it in highly immersive virtual or even real environments. Only if participants had a second distractor task increasing the memory load, the authors found a worse memory performance after walking through doorways. This shows that while the effect seems to be easily replicable, there are conditions under which it seems to be harder. The goal of the present study is to try and replicate a doorway effect using a highly immersive virtual environment.

1.2 The “doorway effect” and context

As mentioned above, Radvansky et al. (2011) provided evidence suggesting that the doorway phenomenon is not barely an effect of context-dependent memory. In their study, they had participants return to the original room where the objects to be remembered were first encoded. Encoding specificity would predict that memory performance would increase again in that case. However, no such effect was found. Notably, this “return” condition implied that participants had to cross the same doorway - or event boundary - twice, and according to the Event Horizon Model, there would still only be two event models activated (first room A, then room B, then room A again). For comparison, they thus also added a “double shift” condition in which participants had to pass through two rooms, resulting in again two event boundaries, but this time three event models (room A, room B and room C). The result was that returning to the original room did not improve memory performance, and there was a large number of errors in the double shift condition. The authors conclude that for the “doorway effect”, it is not the number of event boundaries or doorways that matters, but instead the number of generated event models.

It has to be noted though, that for this study and a majority of the replications, the room context is usually only defined by simple wall colours or at most patterns, and possibly a change in the visual appearance of the floor. While this might visually appear very different, one could question whether this is indeed enough of a difference to be conceptually processed as being different contexts. There are, as previously mentioned, studies that successfully replicate the doorway phenomenon using a real environment (Lawrence & Peterson, 2014; Radvansky et al., 2011), but at the same time, this is not always the case (McFadyen et al., 2021).

Thus, a further goal of the present study is to increase the experience of the two rooms in the task being of a different context. In particular, a highly immersive virtual reality environment is used along with rooms that are visually and semantically different, as indicated by a variety of decorative objects placed in those rooms.

1.3 The present study

While so many replications of the “doorway effect” exist, it is surprising that they almost exclusively use the same task of participants “carrying” one object and putting another one down. This task provides an obvious distinction between an “associated” object being present in two different event models and a “dissociated” object being present in only one. However, focusing on this one task calls into question the robustness and generalizability of the effect, as is evident by the unsuccessful replication by McFadyen et al. (2021). If indeed having items in working memory connected to two different event models reduces their accessibility, this effect should also be found when using a different task that focuses less on the distinction between “associated” and “dissociated” objects.

The present study used a spatial object layout memory task adapted from Bülthoff & Christou (2000). Participants viewed a layout of objects in one room, then walked into another room and tried to detect whether there was a change in the layout. Importantly, while there is no single “associated” object, the memory of the object layout is connected to both the first room (where it is encoded and memorized) as well as in the second room (where the change detection task happens). This means that for this task, the memory for the object layout should in theory be present in two different event models. It follows that if participants walk through a doorway when they switch rooms (and switch event models), they should show a worse memory performance than if there is no doorway and the two rooms seem to be only one - and thus exist in one single event model.

In order to increase the perception of the rooms being either two separate events or one big event, an additional manipulation of room context was added. If participants walk through a door and the semantic and visual context of the room changes, then this should constitute a very prominent event boundary and thus make separating the event models easier. In contrast, if participants walk from one room to another, but there is neither a doorway nor a change in context, then this should lead participants to use only a single event model, and thus exhibiting comparatively higher memory performance.

To examine participants' performance in this task, an immersive virtual reality environment was used. This allows for a more realistic and ecologically valid approach to examining the doorway phenomenon as compared to presenting the task on a computer screen, which is also aided by the use of stimuli that are not abstract, randomly coloured forms (as has usually been used in previous studies), but objects with everyday names or use cases.

2 Methods

The sample size, hypotheses and analyses for this study were preregistered on AsPredicted (#163468, https://aspredicted.org/aj9rf.pdf) before any data was collected. Due to this study being of exploratory nature and part of a Master Thesis, there are several deviations that are compiled in the appendix (see 6.2).

Written informed consent was obtained from all participants regarding the nature of this study and its risks (cyber sickness) as well as the use and publication of the collected data in an anonymous form (see 6.1).

2.1 Participants

A total of 27 participants were recruited for this study, mainly from the pool of students at the University of Tübingen. The sampling procedure was a general recruitment mail to the participant pool of cognitive science and psychology students (which provided almost half of the participants), as well as a "snowball"-recruitment strategy by strongly encouraging participants to inform their peers of this study. All participants received partial course credit ("Versuchspersonenstunden") for their participation.

Two participants were excluded from all analyses due to programming error and incomplete data. The mean age of the remaining 25 participants (15 female) was 20.8 years, range 18 - 29 years. All had normal or corrected-to-normal vision and participants with glasses ($n = 10$) wore them comfortably below the head-mounted display (HMD).

A pre-experiment questionnaire revealed that most participants had only few previous experiences using immersive VR, mostly consisting of participation in other studies or educational settings with low interaction (e.g., exhibition in a museum). Six participants reported not having used VR previously.

2.2 Equipment and Setup

The virtual environment was created using the open-source game engine Godot v.4.1.3 and the community-created VR toolkit Godot XR tools 4.3.0. The experiment was run on a Windows 11 personal computer (AMD Athlon 3000G, Radeon RX570) within the Godot engine. Participants viewed the virtual environment through an HTC Vive Pro HMD. All objects used for designing the virtual environment were retrieved from https://itch.io and were available under a Creative Commons License (CC BY 4.0). A detailed list of the sources can be found in the appendix (section 6.3).

Participants were seated on a revolving chair roughly in the centre of the tracking area of two HTC Vive Pro Base Station 2.0, connected to the PC via Bluetooth. For movement and interacting with the response buttons, they used two HTC Vive wireless controllers. Movement via the controllers was available by pressing the main trigger buttons with their index fingers, providing straight movement forward or backward (right and left controller, respectively) in the direction they were currently facing. Rotation, turning around and movement along curved paths was available by turning on the revolving chair, but was discouraged by the experimenter. This way of movement was selected in order to reduce potential cyber sickness symptoms and enable participants to move easily and quickly within the virtual environment.

2.3 Procedure and Stimuli

This experiment combined a manipulation of the visual and semantic context of the virtual environment with a spatial object layout memory task. Both aspects are described in the following sections separately.

Participants were introduced to the controls and had a few minutes to get used to them by moving freely through the virtual environment. Afterwards, they received an explanation of the experimental task and completed two halves of a training block to make them comfortable with the task and the environment. During the second half of the training block, a black vignette was introduced to reduce peripheral vision during movement and thus to reduce the probability of cyber sickness. Participants could then choose whether to use this setting or not, depending on the degree of cyber sickness symptoms during the training block. If participants responded too slow or did not move quickly enough (see 2.3), those trials were repeated during the training block, resulting in at least 16 valid, completed training trials for each participant before the actual experiment started.

No breaks or block structure was used for this experiment to allow each participant to take self-directed breaks. This was a deliberate decision to make sure that immediate action (e.g., breaks, removing HMD and physically walking through the room) could be taken at any time as soon as any participant reported any sign of cyber sickness.

After the experiment, participants completed a simple questionnaire to record strategies used during the experiment as well as the participants' experience with the VR setup.

Room Context

The virtual environment consisted of two rooms that were either connected by a doorway or not (see Fig. 1). Each room could either resemble a "living room" or a "workshop", providing two different semantic and visual contexts. The rooms were constructed and combined in a balanced way to create the experimental conditions of a 2 (doorway vs. no doorway) by 2 (same context vs. different context) balanced design.

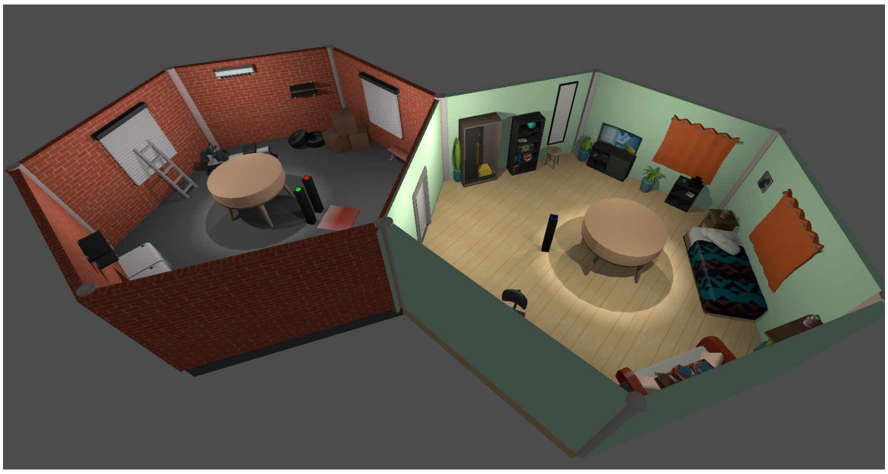

Figure 1: **Example room overview**. Ceiling and ceiling lamps have been removed for this visualization. Two rooms are connected by a doorway (for the ”no doorway” condition, the separating wall and door are removed while everything else stays the same). On the left is an example of the ”workshop” room: This room had a red, textured wall and the decoration were objects like boxes and tires on the floor as well as a countertop, and a washing machine. Almost no small objects are placed as additional decoration. On the right is an example of a ”living room”, consisting of green walls and a textured wooden floor. The furniture are closets, a bed, a desk, and a variety of small decorative objects are scattered at usual positions (books on shelves, laptop on the desk, cushions on the couch). For each room, two different variations were created with slight differences in placement of the furniture and a slightly different selection of decorating objects, in order to increase visual variability, immersion and realism. The room variation was drawn completely at random for each trial. In this example, participants would start in the right ”living room” looking at the table in the centre, and they would have to move through the doorway into the ”workshop”.

Each room was a hexagon with decorating objects defining the context placed along five walls, and a large, circular table in the centre that contained the objects for the memory task. If the two rooms were connected by a doorway, there was a wall with a door that opened by itself when the participant moved close to it (with a slight delay of 0.15 seconds after entering the region in front of the door). This wall did not have any decoration related to the room context except the wall colour.

This ensured that the overall setup and decoration did not change between the two doorway conditions, as well as not placing any objects at the boundary between the two rooms. Regardless of experimental condition, the distance between the rooms and the door location within the wall was identical for all trials, ensuring that the spatial distance travelled when moving between the two rooms was constant.

Participants started each trial facing the table in the centre of the first room, with their back towards the second room so they could not anticipate the presence of a doorway or a context change (in case there was no doorway, and the second room was visible). They ended each trial while facing the table in the second room and having the first room at their back.

Memory Task

The memory task was a change detection task using a layout of different objects, inspired by the memory task by Bülthoff & Christou (2000).

On the table in the middle of each room, seven locations were arranged in a circle in an equidistant fashion. Each of these locations could either be occupied by an object or not, and the locations were exactly the same for each trial. The participants' task was to look at the layout of objects on the table in the first room and remember it, then move to the second room and compare the remembered layout with the layout of objects presented there. They then had to respond whether the object layout was identical or not and afterwards indicate their subjective confidence for the given response (see also Fig. 2). In half of the trials, there was a change in the object layout, while for the other half the object layout was identical between the two rooms. Importantly, a change in the object layout consisted of two objects swapping places, and participants were informed that this was the only change that could happen.

The objects were randomly drawn for each trial from a pool of fourteen objects, with no duplicates within each single trial. The objects were selected from the pool of 3D models available in the 3D asset packs - this ensured that all objects were similar in visual style. These objects were not used for room decoration, but some of them were semantically more related to one of the two room contexts. Importantly, this decision of object selection was made to increase the ecological validity of the experiment: All objects had obvious use cases or names instead of being abstract, randomly coloured shapes. To increase task difficulty, some objects were visually or semantically similar to each other (e.g., circular shape: tape - CD; tools: wrench - hammer).

Trial Structure

In front of the table in the first room was a blue button that started each trial when pressed. Participants were instructed to press the button by moving the controller (and thus their hand in the virtual and physical environment) as though actually pressing the button. Slight haptic feedback was provided for pressing any button by a short vibration of the controller.

Pressing the blue button lifted the cover from the table for a total of 3 seconds (0.5 seconds for movement up and down respectively, 2 seconds no movement at the highest point). Participants then had to turn around at their current position by 180 degrees and move straight onto a mat on the floor of the second room. For completing the whole movement, participants had a total of 8 seconds, starting as soon as the cover of the first table was closed again. Once those 8 seconds had passed, the cover from the table in the second room opened in exactly the same manner as in the first room. In the second room, there were two buttons, which were used to respond whether the layout of objects on the tables had changed or not: a green button to respond there was no change (“GLEICH”, same), and a red button to respond that a change was detected (“VERSCH”, different). Participants had a maximum of 5 seconds to respond after the cover started revealing the second object layout. After interacting with either of those buttons, they disappeared quickly down into the floor, followed by a set of four yellow buttons appearing from the ground. Those buttons were used to record the confidence each participant had in their response for each single trial (“geraten” - “nicht sicher” - “ziemlich sicher”

- “sehr sicher”, guessed - not confident - quite confident - very confident). Participants had a maximum of 5 seconds to give their confidence response, starting when the buttons had appeared completely. The location of the response buttons and their order from left to right was the same for each trial. After pressing one of the yellow confidence buttons, the screen turned black for roughly 2 seconds and participants were placed in front of the blue button in the next trial (see Fig. 2). These timings ensured that participants had enough time to move on their own and with their own speed between the two rooms while simultaneously keeping the retention time for the memory task exactly the same for each participant and trial.

If participants responded too slowly to the memory task or the confidence rating, an error message appeared in front of them to respond a little bit faster. Similarly, if participants moved too slowly and did not stand roughly on the mat in the second room once their movement time of 8 seconds had passed, they were informed to move faster between the two rooms. All those trials were marked as invalid and repeated at the end of the experiment, resulting in a total of 128 valid trials for each participant. Importantly, the experimental condition (doorway and room context combination) was kept for the repeated trials to ensure a balanced design, while the objects and room variations were drawn randomly again. This also ensured that errors did not result in accidental learning over multiple trials by providing a new object layout.

For each trial the response correctness and response time was recorded, as well as the reported subjective confidence and the response time for the confidence decision.

A demonstration of an example trial is available in video format (https://osf.io/5cydj).

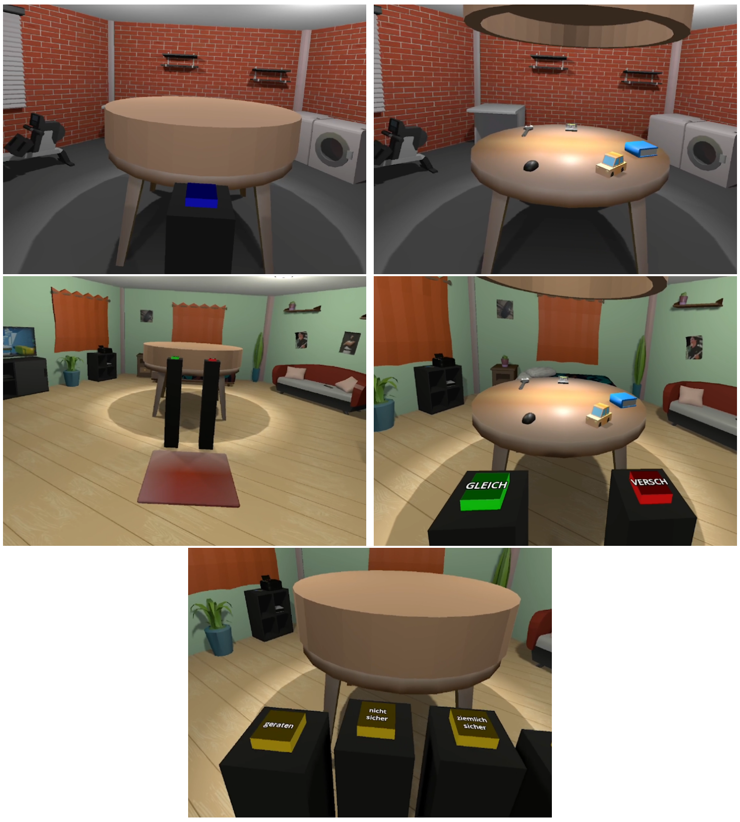

Figure 2: **Trial example**. **Top left:** Participants start with a view of the blue button to start the trial, in front of the table. The table is initially covered. **Top right:** After pressing the blue button, the cover moves up and reveals the object layout to memorize. Note that there is a separate light source illuminating the objects, so that for both the first and second presentation of the objects, the visual image is as similar as possible - additionally, the cover of the table at no point interacts with that light source, as is more evident in the video demonstration of the trial, available online. **Middle left:** After the cover closes again, participants turn around and move into the second room. Their goal location is marked by a red mat on the ground, from which they can comfortably reach the response buttons. **Middle right:** After a constant delay, the cover lifts from this table and participants can give their answer whether the layout changed. **Bottom:** After that response, new buttons appear which participants used to respond how confident they were in their response. Afterwards, the screen turns to black, and participants start in the next room. The experimental condition depicted here contains a context change (red ”workshop” to green ”living room”), there is no doorway.

Task Difficulty

Due to the exploratory nature of this experiment, a slight change to the memory task was made during data collection, which was not preregistered.

The first 18 participants completed a memory task where 5 out of the 7 locations were occupied by a random object. Due to the nature of the task, participants quickly and consistently adapted a strategy of remembering only 4 of those objects, sometimes aided by structuring the layout using the two empty locations, which resulted in a very high task performance (see section 3). Thus, the final 7 participants completed a harder version of the task, where all 7 locations were occupied (see Fig. 3).

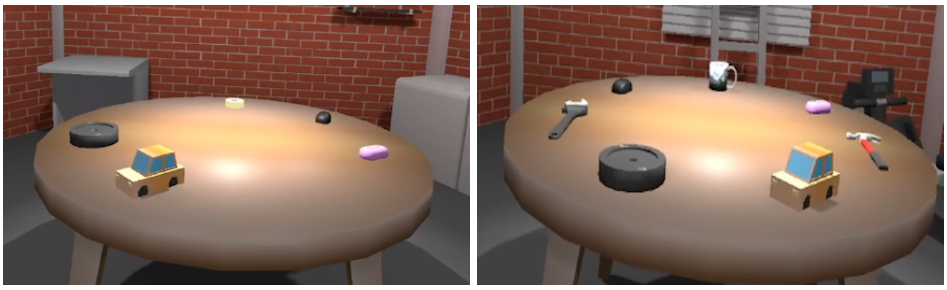

Figure 3: **Task difficulty comparison**. **Left:** Easy task for the first 18 participants. Five different objects were randomly drawn and placed on five of the seven fixed locations. As a result, two empty locations could be present. If there was a switch of objects, it never occured that an empty location was now occupied since this would have allowed a too simple strategy of only remembering the two empty locations. Still, participants usually only remembered four objects, since this allowed to detect any switch between two objects. **Right:** Increased task difficulty for the final 7 participants. All of the seven possible locations are occupied with randomly drawn objects, increasing the number of items that need to be correctly remembered to at least six.

3 Data Analysis and Results

For all following analyses, only the valid trials for each participant are included. There are two trials where the response to the memory task was given with a response time of less than 200 ms, indicating an accidental button press. Those trials are removed, leaving a total of 127.9 trials per participant on average (range 127 - 128 trials). Similarly low response times could be observed for the confidence responses. However, since the confidence buttons were identical for each trial, their position could be anticipated, leading to very low confidence response times. Since no relevant analyses were planned for this variable, no trials are rejected due to low confidence response times.

Note that the following analyses only include the first 18 participants that completed the initial task where only five of the seven object locations were occupied. The remaining seven participants with a more difficult task are analysed separately (see 3.3).

3.1 Response Times and Performance

The overall median response time is 2.73 s, with individual mean response times between 2.23 s and 3.94 s (see Fig. 4). The overall mean response time is 2.85 s ($SD = 0.42$ s). Due to the highly immersive way of responding (by physically moving the hand to the response buttons), there is a very high variability in the recorded response times, possibly masking any effects of the experimental conditions.

The mean percentage of correct responses is 86.3% ($SD = 9.9$%, range 68.0% - 97.7%). As can be seen in Fig. 4, there is no relationship between speed of responses and overall performance.

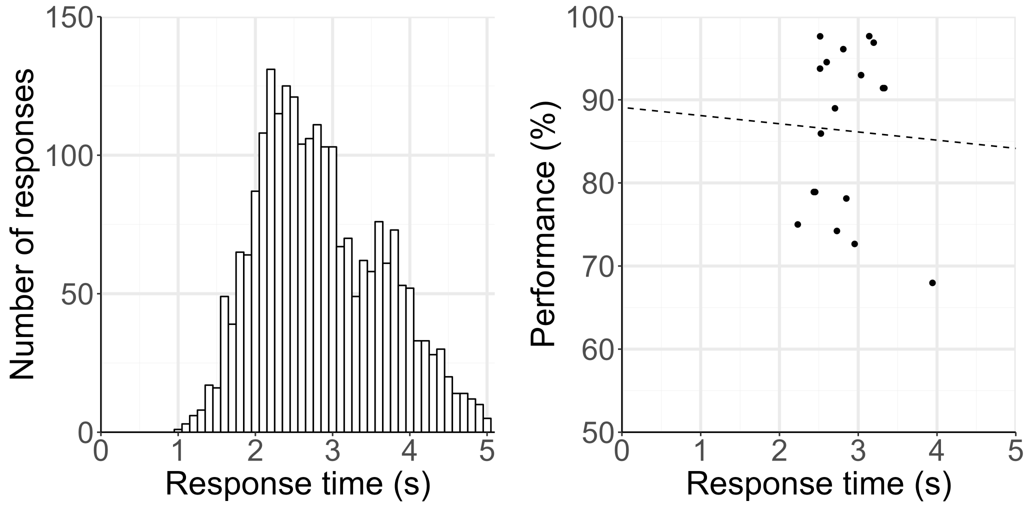

Figure 4: **Response time and performance overview**. **Left:** Response time distribution for all participants, bin size 100 ms. **Right:** Mean percentage of correct responses and mean response times for each participant. The dashed line represents a simple linear regression ($r = -.986$, $p = .868$).

A repeated-measures ANOVA was conducted with the doorway condition (doorway vs. no doorway) and the context change condition (same context vs. different context) as within-subject factors, to determine if the response times for the memory task were influenced by the doorway and context transitions between the two rooms. No effect of doorway ($F(1, 17) = 0.00$, $p = .98$) or context ($F(1, 17) = 0.45$, $p = .51$) was found (see Fig. 5), and there was no interaction ($F(1, 17) = 0.13$, $p = .72$).

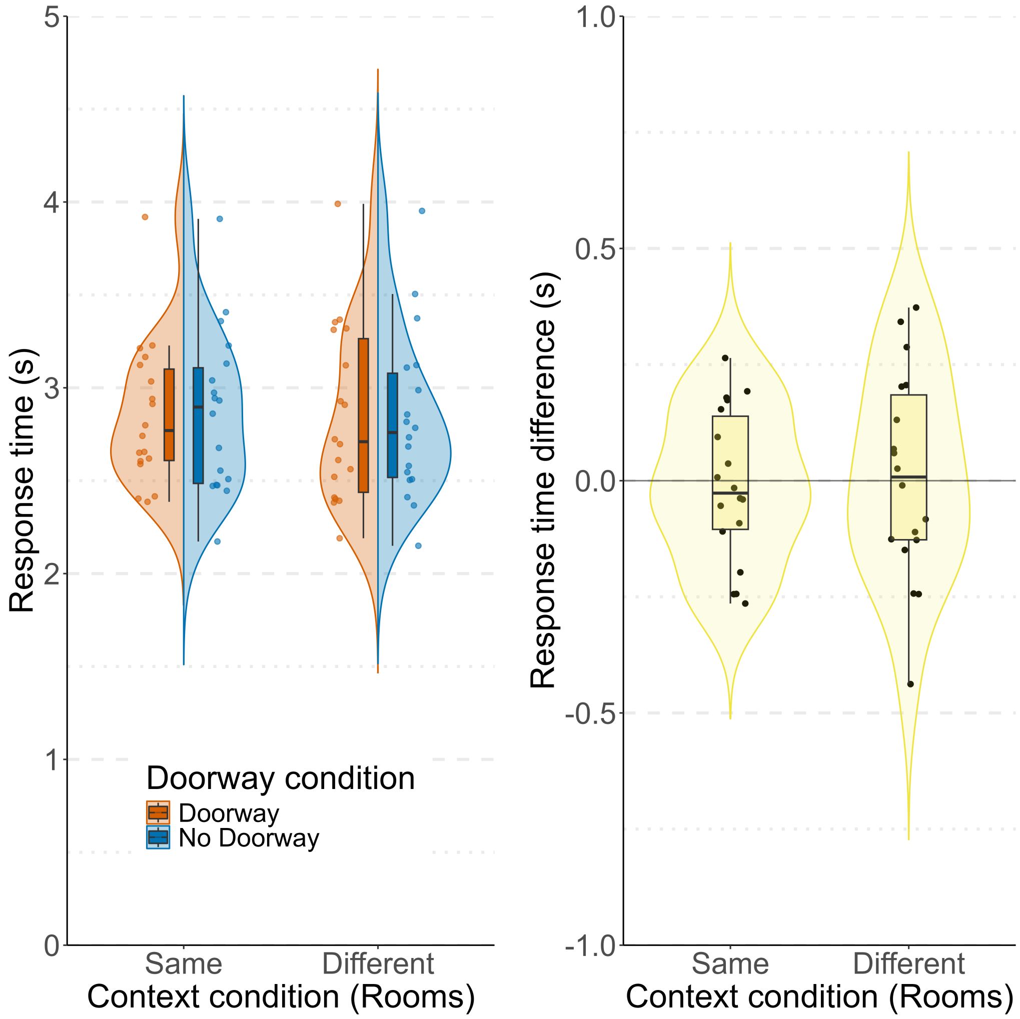

Figure 5: **Response times for doorway and context conditions**. **Left:** Each dot represents the mean response time for one participant, the violin plot in the background visualises the density distribution over all participants. **Right:** This plot shows the individual per-participant differences in response time between the two doorway conditions (no doorway - doorway). Negative values thus indicate a higher response time for the ”doorway” condition.

A second repeated-measures ANOVA with the same setup was conducted on the overall percentage of correct responses for each participant. Again, there was no effect of doorway condition ($F(1, 17) = 1.57$, $p = .23$) or context change

$(F(1,17) = 0.20$, $p = .66)$ and no interaction $(F(1,17) = 0.20$, $p = .66)$, as can also be seen in Fig. 6.

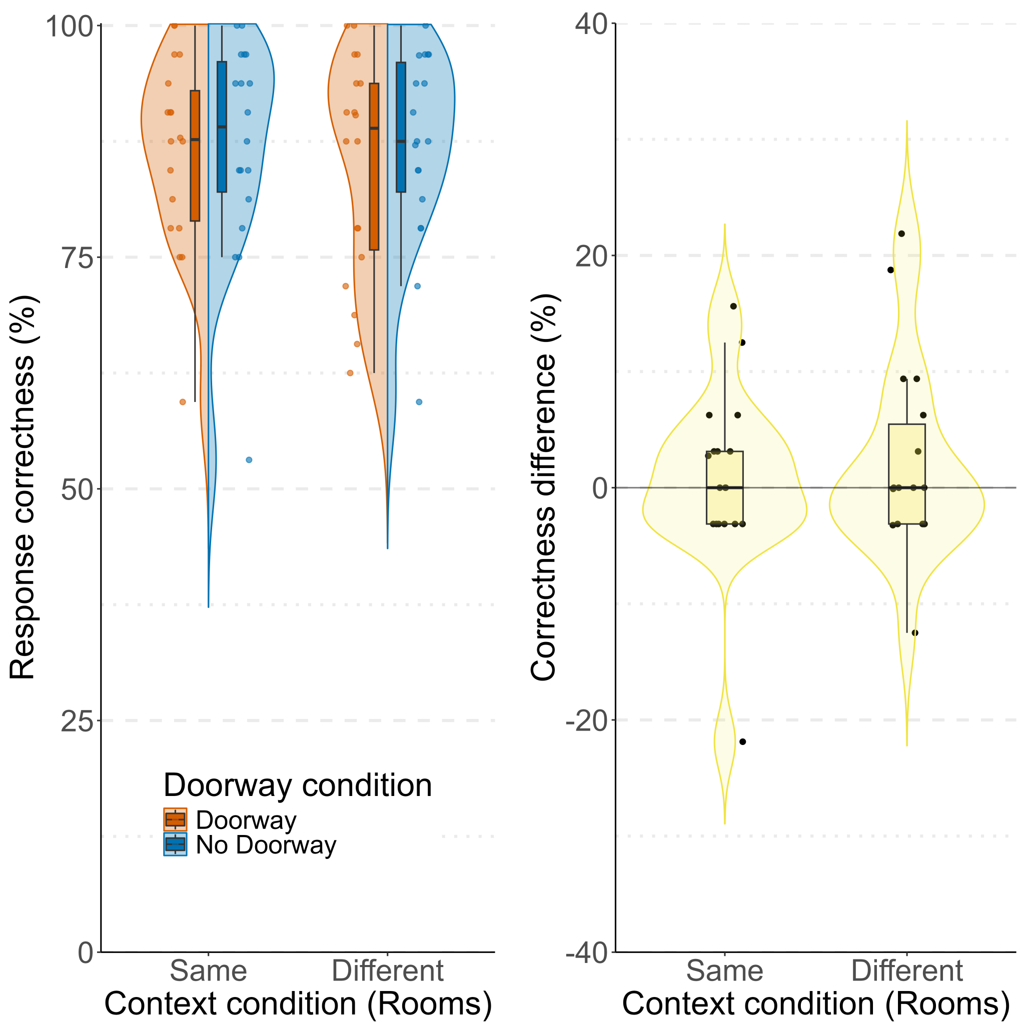

Figure 6: **Response correctness for doorway and context conditions**. **Left:** Each dot represents the mean percentage of correct responses for one participant, the violin plot in the background visualises the density distribution over all participants. **Right:** This plot shows the individual per-participant differences in performance between the two doorway conditions (no doorway - doorway). Positive values thus indicate a higher performance for the ”no doorway” condition.

3.2 Hit Rates

Figure 6 demonstrates the very high number of correct responses regardless of experimental condition for almost all participants. However, the percentage of correct responses takes all trials into account, whether there actually was a change in the object layout or not. In order to take a closer look at the data, an approach based on signal detection theory was employed. Since half of the trials did actually contain a change in the object layout and the other half did not, it was possible to define “hits” as the correct detection of a layout change, and “false alarms” as the incorrect responses to an unchanged object layout. This way, the percentage of correctly detecting the change in the object layout (hit rate) could be analysed separately from those trials without a change.

The mean hit rate is 83.3% ($SD = 13.8$%), with individual hit rates between 59.4% and 98.4%. The corresponding false alarm rates ranged from 0% to 37.5%, with a mean of 10.8% ($SD = 9.3$%). A repeated-measures ANOVA with the hit rate as dependent variable revealed only a small effect of doorway condition ($F(1, 17) = 4.78, p = .04$), but no effect of the context change ($F(1, 17) = 0.02$, $p = .90$) and no interaction ($F(1, 17) = .09, p = .76$). The difference in hitrate between the doorway and no doorway condition is 4.5%, with a higher hitrate if no doorway was present (85.6% vs. 81.1%, see Fig. 7).

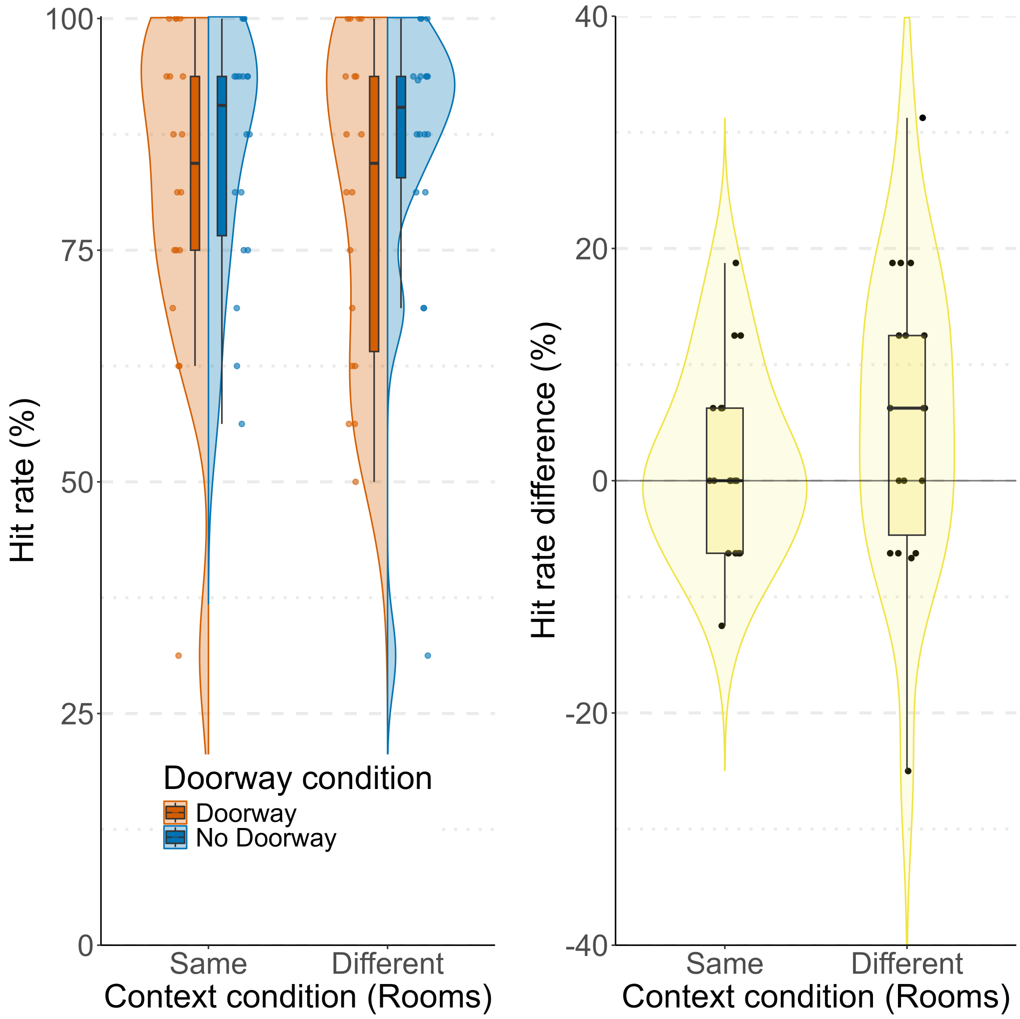

Figure 7: **Hitrates for doorway and context conditions**. **Left:** Each dot represents the mean hit rate for one participant, the violin plot in the background visualises the density distribution over all participants. **Right:** This plot shows the individual per-participant differences in hit rate between the two doorway conditions (no doorway - doorway). Positive values thus indicate a higher hit rate for the ”no doorway” condition.

3.3 Exploratory Analyses

This section contains exploratory analyses as well as the analysis of the final 7 participants with a more difficult memory task.

Confidence Judgements

Participants rated their subjective confidence of their response to the memory task on a 4-point scale. For the following analysis, these confidence judgements were transformed into numerical values from 0 to 3 (0: guess, 1: not confident, 2: quite confident, 3: very confident). Note that participants only used the verbal descriptions to give their responses. Additionally, due to the design of the virtual environment, the confidence buttons appeared with a slight delay after a response to the memory task was given, and the order of the buttons was always identical. Thus, participants usually already reached for the location where the confidence button would be before they were actually able to press that button. This might influence the accuracy of this confidence measure and is the reason why the confidence response times are not further examined.

Using the numerical transformation, the mean confidence of participants in their responses is 2.22, with a range of 1.66 - 2.80 (Fig. 8), showing a clear tendency of participants giving very high confidence ratings. An ANOVA using the numerical confidence rating as a dependent variable revealed no effects of doorway ($F(1,17) = 0.00$, $p = .98$) or context ($F(1,17) = 0.17$, $p = .68$) and no interaction ($F(1,17) = 0.19$, $p = .67$).

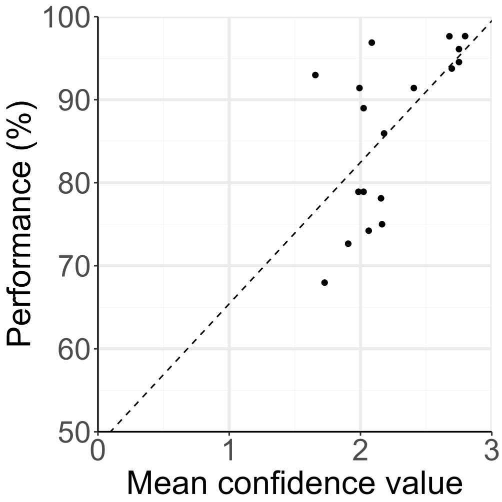

Figure 8: **Confidence ratings and overall performance**. There is a relation between the overall percentage of correct responses and the overall mean confidence of each participant ($r = 17.04$, $p = .005$), with participants showing a higher performance also giving higher confidence ratings on average.

Task difficulty

For the final 7 participants (5 female), a harder memory task was employed. The median response times is 3.02 s, with a range of individual median response times between 2.67 s and 3.48 s (see Fig. 9), with an overall mean response time of 3.06 s ($SD = 0.29$ s). The mean percentage of correct responses is 76.5% ($SD = 14.1$%), with individual performances ranging between 51.6% and 96.1%. Hit rates for this group of participants range from 34.4% to 98.4% (mean hit rate 72.5%, $SD = 21.2$ %), with false alarm rates between 6.3% and 35.9% (mean false alarm rate 19.6%, $SD = 12.1$%). Using the same numerical transformation for the confidence ratings as above, the mean confidence is 2.03 (range 1.66 - 2.66).

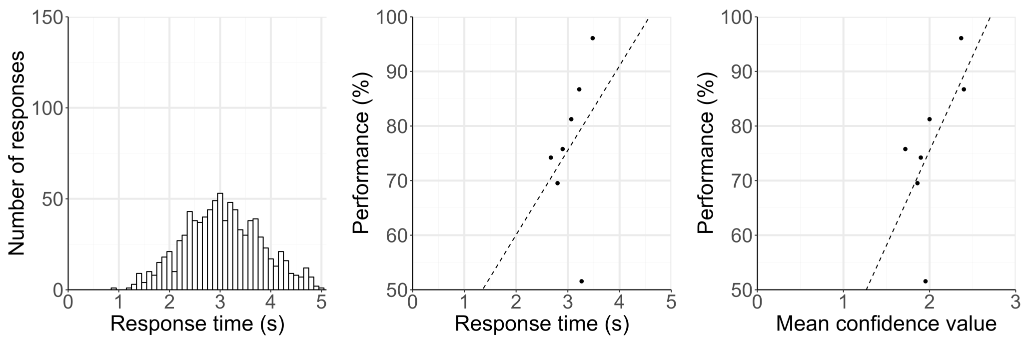

Figure 9: **Response time, performance and confidence overview for increased task difficulty**. **Left:** Response time distribution for all 7 participants, bin size 100 ms. **Middle:** Mean percentage of correct responses and mean response times for each participant. The dashed line represents a simple linear regression ($r = 15.50$, $p = .49$). **Right:** Mean confidence rating and overall performance, with the dashed line representing a simple linear regression ($r = 34.69$, $p = .12$).

For comparability, ANOVAs have been applied to this data in the same way as reported earlier. For response times, no effect was evident (doorway: $F(1, 6) = 3.28$, $p = .12$, context: $F(1, 6) = 0.56$, $p = .48$, interaction: $F(1, 6) = 0.01$, $p = .91$), and there was no effect on the percentage of correct responses overall (doorway: $F(1, 6) = 0.36$, $p = .57$, context: $F(1, 6) = 0.01$, $p = .92$, interaction: $F(1, 6) = 0.92$, $p = .37$). Similarly, no effect of doorway or context on hit rate could be found (doorway: $F(1, 6) = 2.15$, $p = .19$, context: $F(1, 6) = 0.02$, $p = .90$, interaction: $F(1, 6) = 1.76$, $p = .23$). Surprisingly, there was a significant effect of the doorway condition on the confidence ratings ($F(1, 6) = 10.03$, $p = .02$), with no effect of context ($F(1, 6) = 1.16$, $p = .32$) and no interaction ($F(1, 6) = 1.78$, $p = .23$). While participants were slightly more confident in the “no doorway” condition, this result should not be deemed very important due to the small sample size and also the small numerical difference between the conditions (numerically transformed mean confidence: 2.07 vs. 1.98 for “no doorway” vs. “doorway”, respectively).

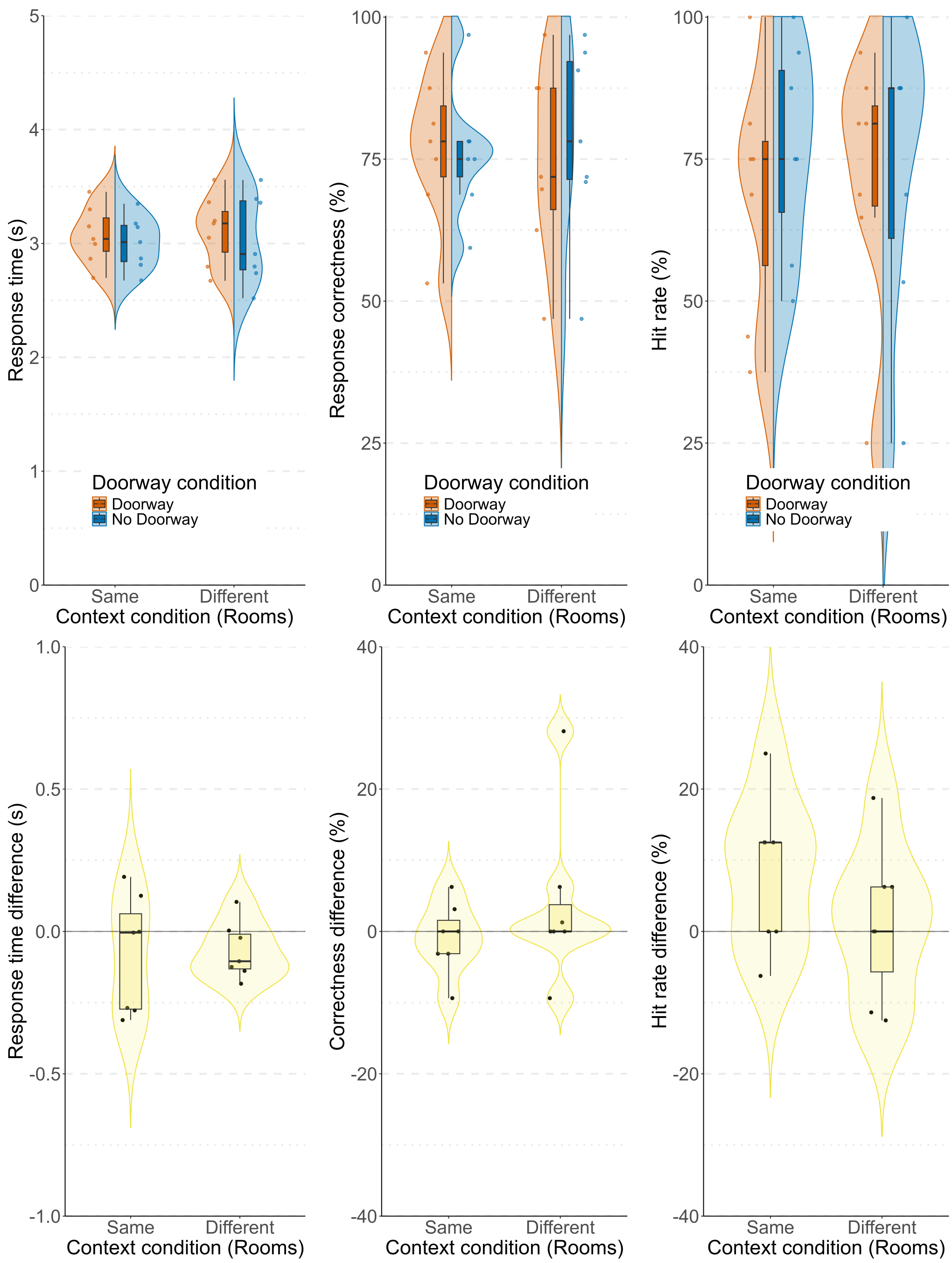

Figure 10: **Response time, response correctness and hit rates for difficult memory task**. These figures follow the same structure as Figs. 5, 6 and 7. The bottom row shows the individual, per-participant differences between the doorway conditions (no doorway - doorway). Note that the sample size is smaller than for the results reported earlier. **Left:** Response times. **Middle:** Response correctness. **Right:** Hit rates.

Lowest performing participants

The previously reported analyses show that no clear effect of doorway or context change on memory effect was present in this study. However, in both memory tasks (easy and difficult), there are a few participants with very high percentages of correct responses. It might be reasonable to assume that they used very effective memory strategies or experienced the task as too easy overall. This might lead to a ceiling effect that masks the presence of any result of the experimental manipulation. In an additional exploratory analysis, only the worst performing participants were analysed. Note that this analysis combines the two task difficulties, so all results presented here should be interpreted with care.

Visual inspection of the overall summary of performance for all participants (see Fig. 11) was used to define the limit for low-performing participants. This limit was chosen to be 80% overall correct responses, in order to provide an acceptable sample size ($n = 11$) for this exploratory analysis. This means that for the following analysis, only participants were included that responded correctly to the memory task in less than 80% of the trials, from both task difficulties (number of participants included from easy task: $n = 7$, hard task: $n = 4$).

For these participants, the median response time is 2.73 s, the mean response time is 2.84 s ($SD = 0.46$ s, range 2.32 s - 3.94 s). The mean percentage of correct responses is 72.4% ($SD = 7.8$%) with individual values in the range between 51.6% and 78.9%. Hit rates range from 34.4% to 84.4% (mean hit rate 66.2%, $SD = 14.2$%) with false alarm rates between 9.4% and 37.5% (mean false alarm rate 21.3%, $SD = 10.1$%). The mean confidence rating is 1.95 (range 1.72 - 2.16).

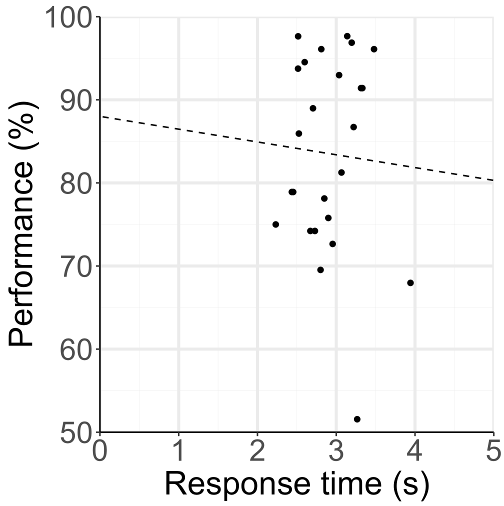

Figure 11: **Overall performance and response times for all participants**. This combines the participants from the easy memory task ($n = 18$) and the hard memory task ($n = 7$).

Again, ANOVAs were applied with the doorway and context conditions as within-subject variables on response times, response correctness, hit rates and confidence ratings. There was no effect on response times (doorway: $F(1,10) = 0.00$, $p = .96$, context: $F(1,10) = 1.61$, $p = .23$, interaction: $F(1,10) = 0.05$, $p = .83$) or response correctness (doorway: $F(1,10) = 3.17$, $p = .11$, context: $F(1,10) = 0.61$, $p = .45$, interaction: $F(1,10) = 1.35$, $p = .27$). However, there was a significant effect of doorway condition on hit rate ($F(1,10) = 12.36$, $p = .0056$), with no effect of context ($F(1,10) = 0.14$, $p = .72$) and no interaction ($F(1,10) = 0.27$, $p = .62$). When averaging over the context conditions, the hit rate difference between the two doorway conditions is 9.4%, with a higher hit rate for the "no doorway" condition (70.9%) than the "doorway" condition (61.5%).

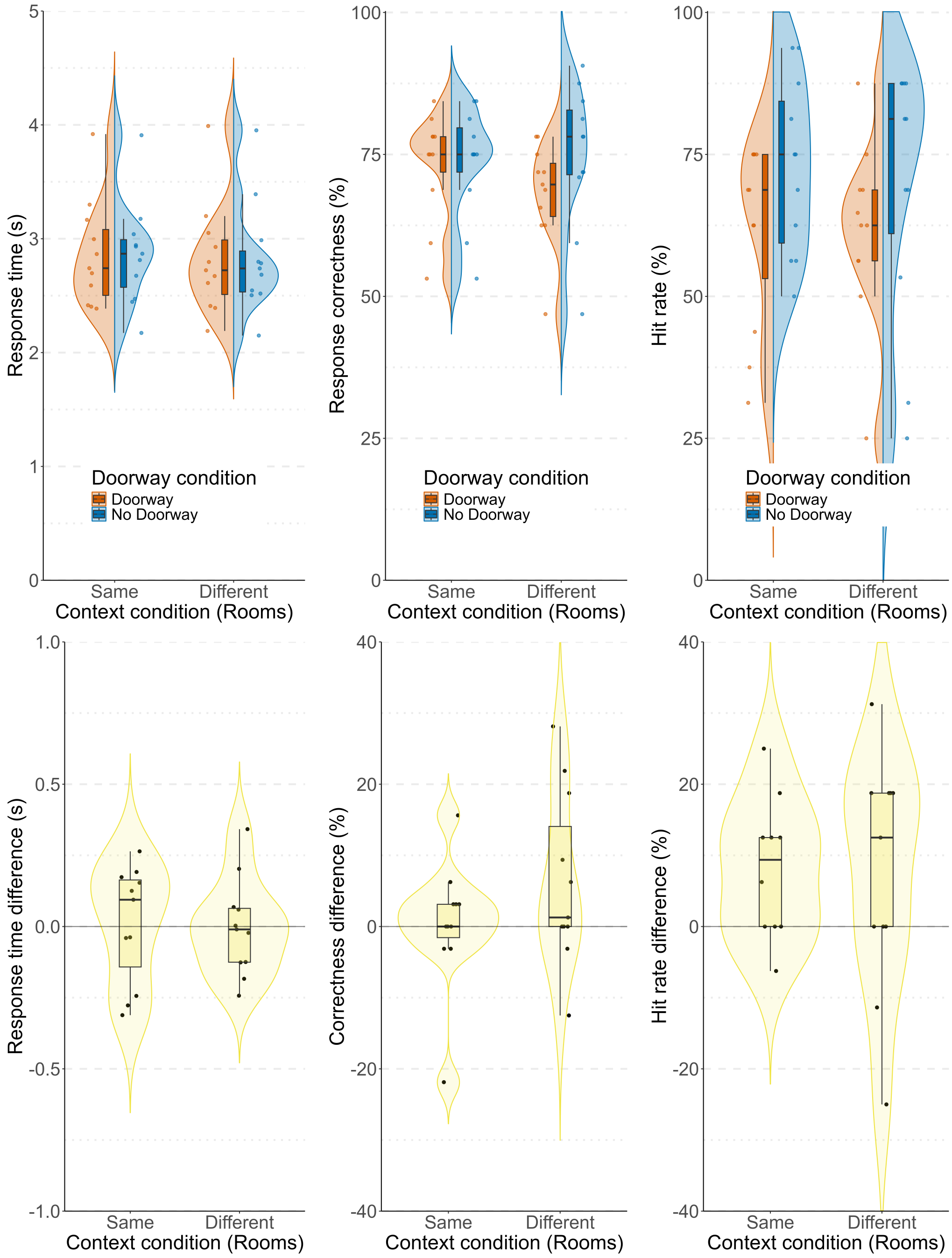

Figure 12: **Response time, response correctness and hit rates for lowest performing participants**. These figures follow the same structure as Figs. 5, 6 and 7. The bottom row shows the individual, per-participant differences between the doorway conditions (no doorway - doorway). Note that this combines participants from the easy and difficult task. **Left:** Response times. **Middle:** Response correctness. **Right:** Hit rates.

Questionnaire

The post-experiment questionnaire contained an open question regarding the strategies used by the participants for the memory task, as well as 7-point scales for rating their VR experience.

As already mentioned previously, the dominant strategy to remember the objects in the easy task was to remember only 4 of the 5 items, usually by mentally listing them either in clockwise or counterclockwise order. The items were usually remembered by name or colour. Similar strategies were used by the participants with the difficult memory task.

Table 1 contains the questions from the questionnaire as well as the participants' responses. There are four sections with selected items taken from the Virtual Reality Neuroscience Questionnaire (Kourtesis et al., 2019). The sections focused on subjective immersion, the usability of the controls, the usefulness of the initial training trials as well as symptoms of cyber sickness. Since only a subset of items from the questionnaire were used in this study, no statistical analysis of responses is presented here.

Responses indicate that the quality and immersion of this study's virtual environment was perceived as neutral to high. Using the controls and interacting with the environment was experienced as being very easy, and the initial training trials were rated as very helpful overall. Notably, no participant stopped the experiment due to cyber sickness, and the usual cyber sickness symptoms were mostly rated as being mild.

	Extremely low	Very low	Low	Neutral	High	Very high	Extremely high
What is the level of immersion you experienced?		1	2	5	14	2	1
What was your level of enjoyment of the VR experienece?			3	7	11	4	
How was the quality of the graphics?		3	8	9	5		
How was the quality of the VR technology overall (headset, controller, etc)?		1	1	7	13	3	
	Extremely difficult	**Very difficult**	**Difficult**	**Neutral**	**Easy**	**Very easy**	**Extremely easy**
How easy was using the control of the navigation system in the virtual environment?					5	17	3
How easy was moving to your goal locations in the virtual environment?			1		8	11	5
How easy was using the interactive elements in the virtual environment?			1		6	13	5
	Extremely unhelpful	**Very unhelpful**	**Unhelpful**	**Neutral**	**Helpful**	**Very helpful**	**Extremely helpful**
How helpful were the training trials at the start of the experiment for interacting with the virtual environment?				1	4	9	11
	Extremenly intense	**Very intense**	**Intense**	**Moderate**	**Mild**	**Very mild**	**Absent**
Did you feel dizziness?				5	2	13	5
Did you feel nausea?		1	1	3	2	4	14
Did you feel disoriented?				1	4	10	10
Did you feel tired?				7	4	6	8

Table 1: **Questionnaire responses**. Each cell indicates how often that option was selected by all 25 participants.

4 Discussion

This study aimed to explore the "doorway effect" or location updating effect using an immersive virtual reality environment and a memory task that has previously not been used for studying this phenomenon.

The location updating effect is a disruption in cognitive processing, usually examined by having participants move from one location to another while working on a memory task. Previous research has consistently shown that memory performance is worse after passing through a doorway into the new location (Pettijohn & Radvansky, 2016; Radvansky et al., 2011; Radvansky & Copeland, 2006). Importantly, this effect can usually be observed even if the memory load for the participants only consists of two objects: one associated, "carried" object and one dissociated, "put-down" object - with a worse memory performance for both objects, but a larger effect on the "associated" object. In order to more closely examine this phenomenon, the present study used a more complex object layout memory task, in which participants had to decide if a spatial arrangement of objects that they viewed in two rooms had changed.

This study could not provide convincing evidence for a location updating effect using this new memory task. Only when analysing the hit rate instead of overall performance, a small effect could be found that indicated reduced memory for the object layout after passing through a doorway. Notably, this effect was slightly more pronounced for the lowest performing participants, indicating that under higher working memory load, a more easily observable location updating effect can be expected, in line with the work by McFadyen et al. (2021).

4.1 Response times and response correctness are unaffected by doorway and context

For the response times, no effect could be found. This is different in comparison to previous studies examining the "doorway effect" (e.g., Radvansky et al., 2010), where usually for the doorway condition, slower responses were given. However, the present study used a highly immersive way of participants interacting with the response buttons - instead of pressing a button on the controller, they had to physically move their whole arm to press the button in the virtual environment. While this increases the immersive experience of the environment overall, it also heavily increases the response time range and variability. Thus, any effect that might be present on the response times could not be found with this study's experimental design. Note that while it would be possible to have participants answer using buttons on the controllers, they already had to get used to the controls for moving through the environment. Making additional buttons on the controllers relevant for the task might overall influence the perceived task difficulty and interfere with the participants' ability to navigate the virtual environment.

Also, no effect of the doorway condition or the change in room context could be demonstrated. The classic doorway phenomenon studies usually show that the correctness of responses to the memory probe is reduced after passing through a doorway, especially when comparing the "associated" to the "dissociated" objects (e.g., Pettijohn & Radvansky, 2015). Such an effect might indeed also be present for the experimental design in the present study, but due to participants using very effective memory strategies, it might be hidden. Importantly, for the first and larger part of this experiment, participants consistently used the strategy of only remembering four objects, which is not a very high task difficulty or memory load. One could argue that the original experimental design for the doorway studies (picking up and carrying only one object at a time) leads to participants effectively only remembering two objects and thus the number of objects in the working memory is not a very relevant factor. However, in those experimental designs, the objects the participants interacted with were abstract shapes with different colours (e.g., a red pyramid and a blue cube), and the memory probe might either be one of those objects or a recombination (e.g., a red cube). Due to this design, there is a high probability of confusing the objects and colours, thus increasing the overall task difficulty - even if, in theory, only two objects are task-relevant. The present study however used differently coloured objects that could easily be identified or given a name (e.g., toy car, wrench, pink soap) and might thus have drastically lowered the overall task difficulty.

4.2 Doorways and increased memory load reduce hit rate

While no effect on the overall percentage of correct responses could be found, the data was examined additionally using a signal detection based approach. For this, since 50% of the trials did contain a change in the object layout and 50% did not, it was possible to define hits (correctly detecting a change in the layout), misses (failing to detect a change in layout), false alarms (incorrectly responding the layout had changed if it was the same) and correct rejections (correctly identifying an unchanged layout as being the same). While this halved the number of trials included in this second analysis, it also revealed a small effect of the doorway condition on memory performance as measured by hit rate. In particular, participants gave 4.5% more correct responses if there was no doorway between the two rooms. This effect, while significant, is in practice extremely small (4.5% correspond to roughly 3 out of 64 trials). However, McFadyen et al. (2021) also examined the doorway effect using this definition of hits and misses and could show a doorway effect. Notably, their approach using signal detection theory might be relevant for a further examination for this study's memory task, since this way it would be possible to detect whether an overall reduction in memory performance (as measured by overall percentage correct responses) might be due to a reduction in hit rate or an increase in false alarm rate.

Additionally, in the second part of this study, participants were presented with a harder version of the memory task. They now had to remember a layout of seven objects, instead of only five. While no significant effects of doorway or context change could be found for these participants, there was a significant, but again very small difference in their confidence ratings. Previous research has not focused on evaluating subjective confidence or metacognition for the doorway phenomenon, but this might in fact be an option for further research. While response correctness measures actual memory performance, taking a look at metacognition might reveal the subjective perceived difficulty of the different experimental conditions. In fact, Seel et al. (2018) did not use confidence, but related measures to examine the difference of "remembering" (less confident) versus "knowing" (more confident) responses for a memory task in combination with the "doorway effect". They demonstrated that passing through a doorway reduces "remembering" (higher confidence) responses, while "knowing" (lower confidence) responses were unaffected.

This, in addition with the previously mentioned work of McFadyen et al. (2021) and this study's failure to clearly demonstrate a "doorway effect" shows that this phenomenon might not be as strong and reliable as might be expected by the number of replications that mostly all use the same memory task.

McFadyen et al. (2021) could replicate a "doorway effect" only using an experimental condition with an increased memory load, and so the data collected for the present study have also been analysed using memory load as a measure. In particular, it was assumed that participants exhibiting an overall lower number of correct responses are either struggling with the task difficulty or do not use very effective strategies - both indicators that they might work under a higher working memory load. For this, only participants with less than 80% correct answers overall have been analysed, and indeed this was the condition where the biggest effect of the presence of a doorway on memory performance could be found - participants had a lower hit rate (61.5%) for the doorway condition as compared to the "no doorway" condition (70.9%). While this result is only exploratory, this might indeed indicate the presence of a ceiling effect, with participants performing too well in the task not being influenced by the doorway or environmental context conditions.

4.3 Limitations and future research

While previous studies mainly examined the location updating effect using a non-immersive virtual environment (by presenting the experiment on a computer screen), here an immersive VR experience was created. While no effect of the room context on the memory performance could be demonstrated, this study still shows that virtual reality (VR) is a cheap and easy-to-use tool for examining cognitive processes, especially if the spatial layout and structure of an environment is of interest.

Regarding the underlying theory of event cognition, in particular the Event Horizon Model, the present study did not reveal any significant or unexpected information. Rather, the results should be taken as an indication that although there might be a consistent effect of doorways on “associated” objects being present in multiple event models (in comparison to “dissociated” objects), this effect fails to emerge once there is no explicit association of the objects in the working memory. The assumption for the current experimental design was that if the object layout is presented in two different rooms, it is also connected to two different event models, this might be questioned when looking at the results. One explanation might be that passively viewing the objects on the table, without interacting with them, might fail to “associate” them to the mental event models. A possibility to examine this would be to have participants “carry” the whole layout, for example by providing a box containing the different objects. However, considering the verbal feedback and the reported strategies of the participants, they might have done something conceptually similar already - they usually used a strategy of mentally repeating or visualising a list of objects while walking, which could use a similar mental representation as “carrying” those objects. Notably, previous experiments communicated the notion of “carrying” the associated object between the rooms only via visual information on a monitor screen, which might arguably constitute the same level of “association” as mentally repeating a list.

Although Radvansky et al. (2011) presented evidence that the level of immersion does not affect the doorway phenomenon, this could still be an area to explore in future studies. Since we are daily walking through real environments with doors and rich semantic and visual context changes, we might actually be too experienced in countering the effect resulting from crossing event boundaries. Using artificial environments presented on screens and using abstract, constructed objects as stimuli might result in a very unusual, “laboratory”-like experience that thus creates an artificial “doorway effect”. Thus, by using highly immersive virtual environments and practically more relevant memory tasks and stimulus objects, future research could and indeed should consider the ecological validity of such experiments.

4.4 Conclusion

While previous work has repeatedly and reliably replicated the “doorway effect”, this study shows that this effect is not easily transferable onto an object layout memory task. Still, the results presented here should be considered as a first baseline for a new line of experiments on the doorway phenomenon using different experimental tasks. With immersive virtual reality, there exists a cheap and effective way of examining phenomena of cognitive processing in a more applied and realistic setting.

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6 Appendix

6.1 Availability of data and materials

The preregistration for this study, the experimental code, datasets generated and/or analysed during the current study as well as the source files for this report are available in this Open Science Framework repository: https://osf.io/kz8a6/, also available via https://doi.org/10.17605/OSF.IO/KZ8A6.

Also available separately on OSF:

- the preregistration (https://osf.io/xcsvg)
- a video demonstration for a single trial (https://osf.io/5cydj)

6.2 Deviations from preregistration

Any deviation in this study from the preregistration is reported here.

Number of participants

Originally, the goal was to record at least 30 participants. However, this number is not based on a power analysis, since the present study uses a completely new combination of experimental setup and task, so the effect size could not reliably be estimated. Thus, 30 was chosen as this is a common number of participants for VR studies, considering potential exclusions due to cyber sickness. This number could not be reached due to time and resource limitations for this Master Thesis.

Fortunately, no participant had to stop the experiment due to cyber sickness, resulting in a final number of 27 participants, 25 of which are included in the reported analyses.

Task difficulty

During data collection, preliminary examination of the first 18 valid participants revealed no observable doorway or context effect as well as a very high task performance overall. Examination of the questionnaires also revealed that participants consistently used a very effective strategy for remembering, leading to the suspicion that the task might be too easy. Due to his being a Master Thesis of highly exploratory nature, a change in task difficulty seemed to be appropriate to maximise the information gained from this experiment.

Exploratory Analyses

Additional analyses were mentioned in the preregistration for this study that were ultimately not executed. First, since no clear effect of doorway or context on memory performance was found, there was no reason to define boundary strength as a new variable, as the results would not have been changed. The conceptual idea, for potential future research, would be to vary the strength of the event boundaries. In particular, the presence of a doorway that has to be manually opened in combination with a very salient context change might be interpreted as a very strong boundary. The weakest possible boundary would then be one single large room, and, importantly, there could be steps created in between by having a salient context change but no doorway. This in turn could then be examined if it were a weaker or stronger event boundary than a doorway separating two contextually extremely similar rooms.

Second, no analyses were conducted on the relationship between objects and room contexts. Since the present experimental setup took around one hour to complete, an additional experimental condition with objects either belonging to one room context or another would have drastically increased that time. Since the experiment took place in an immersive virtual reality using a head-mounted display, this could potentially drastically increase the degree of cyber sickness symptoms in participants. This analysis has thus been skipped, since the data would only contain a very small number of trials that could be examined for effects of the presented objects.

6.3 3D Assets

The walls, floors and roofs for each room were created and modelled using the open-source creation suite Blender 4.1. All other objects and 3D models were retrieved from the sources below and afterwards combined, scaled, and adjusted using Blender.

Objects used as stimuli, as well as those used to decorate the rooms were selected from the following asset packs, all retrieved November 6, 2023:

- https://styloo.itch.io/classroom-asset-pack
- https://vnbp.itch.io/low-poly-3d-gaming-set-vnb
- https://vnbp.itch.io/low-poly-3d-office-set-vnb
- https://vnbp.itch.io/low-poly-3d-office-set-2-vnb
- https://vnbp.itch.io/low-poly-gym-set
- https://vnbp.itch.io/low-poly-home-set

Selbstständigkeitserklärung

Hiermit erkläre ich, dass ich diese schriftliche Abschlussarbeit selbstständig verfasst habe, keine anderen als die angegebenen Hilfsmittel und Quellen benutzt habe und alle wörtlich oder sinngemäß aus anderen Werken übernommenen Aussagen als solche gekennzeichnet habe.

Ort, Datum Unterschrift