Using Virtual Reality to Unpack the Benefits of Context-Dependent Memory

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How does our environment impact what we will later remember? Early work in real-world environments suggested that having matching encoding/retrieval contexts improves memory. However, some laboratory-based studies have failed to replicate this advantageous context-dependent memory effect. Using virtual reality methods, this work identified circumstances when context-dependent memory effects were most likely to be found. In Study 1, I examined the influence of memory schema and dynamic environments. Participants (*N* = 240) remembered more objects when in the same virtual environment (context) as during encoding. This benefit to recall memory, however, traded-off with falsely 'recognizing' more similar lures. Experimentally manipulating the virtual objects and environments revealed that a relevant object/environment schema aids recall (but not recognition), though a dynamic background does not. In Study 2, I examined whether grasping and interacting with objects would benefit recognition memory, compared to merely looking at the objects. Participants (*N* = 60) were no more likely to correctly recognize objects that they were able to grasp when making judgments about whether they had been previously seen or not. Furthermore, the virtual reality paradigm was designed to be employed not only for in-lab data collection (Study 1 and 2), but also for remote, world-wide data collection. Advantages and disadvantages of implementing this type of remote virtual reality data collection procedure are discussed. The findings presented here further our understanding of when and how context affects our memory through a more naturalistic approach to studying such effects.

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Preface

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1.0 Introduction

Memories store our connections to the past and are useful for both basic tasks such as remembering where we put our phone charger and more emotional events such as one's wedding day or the birth of a child. We are able to remember information that we both deliberately and incidentally encode, while other times forget things we intended to remember. What are the drivers then for which information eventually gets remembered (and which, unfortunately, does not)? Such information can be met across a number of different contexts: on a bus, in a classroom right before taking a test, or when casually walking through a park. Our ability to remember this information is impacted both by the context in which we encountered it, and also where we try to remember it (Ranganath, 2022).

1.1 Context

Each of the examples described above may constitute a particular context in which we might learn new information. This is, however, only one piece of the context puzzle. For example, remembering where we put our phone charger refers to the spatial/location aspect of a context. Comparatively, one's wedding day is tied to a specific window in time – the temporal context. Other uses of context may refer to the cognitive and/or mental state of a person at the time of learning.

Contexts can provide useful cues to memory retrieval. Words previously learned at the same time as each other are more likely to be remembered in conjunction than words which had been more disparately learned (Howard & Kahana, 2002). Relatedly, as one incorporates more information into a current context, that context slowly begins to take on more features of the new information. Additionally, the contributions of other information which may no longer be as relevant diminishes (Polyn & Kahana, 2008). For example, within the context of a word list containing “eagle”, “dove”, “parrot”, one may additionally think about related features such as wings, beaks, flying due to their semantic associations (Kraut et al., 2002). However, if the word list is updated with “tiger”, “shark”, and “gerbil”, we would expect a shift from more bird-focused representations to more general animal features (Polyn & Kahana, 2008).

The ways in which contexts aid memory is not unique to temporal contexts, but can extend to spatial contexts as well (Pacheco et al., 2017). In a similar manner, spatial contexts can also be updated as new information is gleaned from a given situation. For example, a drum set may not exist within the typical context of a classroom. However, if a new teacher is hired, who was previously a member of a rock band, the classroom context for her students will plausibly be updated to now reflect the addition of a drum set and concert posters on the walls. These representations could then serve as new retrieval cues for information learned in that room. The role that these cues within a context may play in benefitting (or hindering) memory retrieval is the focus of the present work.

1.2 Context-Dependent Memory

The *context-dependent memory effect* is a phenomenon in which memories are more likely to be retrieved when the context of encoding matches that of retrieval (Smith & Vela, 2001). In a now classic demonstration of this effect, Godden and Baddeley (1975) had participants recall a list of words, after learning them either underwater or on land. Participants remembered more words when placed in the same, compared to different, context (e.g., encoding and retrieval both underwater compared to encoding underwater and retrieval on land). Though initial well-known studies supported the idea of the context-dependent memory effect, some subsequent laboratory-based studies have failed to replicate these findings. We have yet to fully determine under which conditions and what driving factors lead to context-dependent memory effects.

To better understand the basis of context-dependent memory effects, it is helpful to first examine what systems are at play when someone attempts to remember something. The encoding specificity principle (Tulving & Thomson, 1973) postulates that when retrieving something from memory, we draw on any information that may have been initially encoded in conjunction with that to-be-remembered item. This information can then later serve as a retrieval cue, allowing us to remember the item in question. This principle serves as one of the earliest explanations for how memory declines after a change in environment: the necessary cue is no longer present. There is, however, some ambiguity about what may make that additional information more or less likely to be encoded in conjunction with the desired item.

In Godden and Baddeley's study involving differences in retrieval performance between dry land and underwater (1975), one can imagine a number of key differences between those two contexts. Could the act of breathing (or not) serve as a cue for the to-be-remembered information? Perhaps the feel of the cool water against one's skin, the visual distortions of peering through murky lake water, or the presence of background animals could all theoretically act as cues to aid in subsequent memory.

Perceptually rich environments, such as the ones just described, have been known to affect attention and visual processing of items within them (Wang et al., 2021). Recent studies have suggested that adding visual richness to a context could be a contributor to context-dependent memory effects (Isarida & Isarida, 2014). In one such study, videos were used as background context for to-be-remembered words (Smith & Manzano, 2010). The inclusion of these dynamic features more closely resemble the environments in which we typically encounter objects. A possible explanation for these findings is that videos provide more opportunities to encode the context (i.e., greater encoding specificity), leading to a stronger association with the context. Previous research has shown that emphasis placed on the context during encoding can moderate context-dependent memory effects (Bjork & Richardson-Klavehn, 1989; Isarida & Isarida, 2014). Participants in Smith and Manzano's experiments, however, were explicitly instructed to pay attention to the videos, limiting the conclusions that can be drawn about explicit versus incidental encoding of such contexts (2010).

One potential explanation as to when contexts matter, stems from the *overshadowing* & *outshining* theories (Smith & Vela, 2001). These ideas posit that, like the encoding specificity principle, the impact of the context depends on the presence (or absence) of other factors which can redirect attention, specifically during learning (overshadowing) or retrieval (outshining). These theories are so named because they give particular credit to the other potential cues which can be bound with the to-be-remembered information. For example, if learning words that are all semantically related, the overshadowing theory suggests that the context in which one learns them will be less relevant than if the words were entirely unrelated from each other. In this situation, the semantic relatedness between the words would *overshadow* the feature of the environment in which they were learned, thus resulting in a less pronounced context-dependent memory effect. Conversely, the outshining theory predicts that decreases in context-dependent memory effects are the result of non-contextual features aiding in memory retrieval (as opposed to a reliance on the encoding/retrieval context). This helps to explain why context-dependent memory effects are more often observed in free recall – fewer features are present that could help cue the to-be-recalled information (Smith & Vela, 2001). In recognition memory tests, for example, the first in an association word-pair acts as a much stronger cue to memory than the peripheral encoding/retrieval context.

Both of these theories provide justification and can help us make predictions about when we might expect to observe context-dependent memory effects. Additionally, they highlight an important question relating to context-dependent memory effects and distinctions in the memory process: should we be focusing more on factors present during encoding, or retrieval, when studying context-dependent memory effects?

Recently, context-dependent memory effects have been observed within recognition memory tests using a clever experimental design. The approach unveiled a benefit *but* also a drawback in memory (Racsmány et al., 2021). Using images of objects superimposed over unrelated backgrounds, the authors showed that keeping the same contexts was helpful for recognizing that an object had been seen before. Perhaps surprisingly, however, keeping the same context also led to a disadvantage in making false alarms. This could be because people may have over-generalized or overestimated their knowledge about an item they think they had seen before. The matching context may be introducing a false sense of familiarity leading to worse detection of subtle differences in items (e.g., differences between a prototype and an exemplar for a given object). When contexts are different, we no longer have as many (if any) matching contextual cues, and therefore must rely only on our knowledge of the object to correctly recognize it.

Lastly, prior research has also found that moving to the same physical location is not completely necessary and that simply adjusting one's mental representation of a context can be enough to induce context-dependent memory effects (Smith & Vela, 2001; Bramão et al., 2017). Bramão and colleagues found better memory recall when the encoding and recall contexts matched, compared to when the contexts were different. Importantly, they observed this effect when the contexts were physically reinstated (same background images behind memory cue) *and* when they were only mentally reinstated (provided with context label instead of background image). This work suggests that people are indeed drawing on the semantic representations of a context. Yet a question still remains as to what exactly are people reinstating in their mind. For example, is the to-be-retrieved information associated with the physical features of a context that one might be reinstating or is the context-item relationship that could be the key. These questions have important implications for how such a context is stored in memory, and importantly for the context-dependent memory effect, may affect how objects are integrated into such a context to allow them to be better remembered.

1.3 Schema for Environments and Objects

Schema, and specifically the relevance of to-be-remembered items to their environment, could be an important feature to evoke pronounced context-dependent memory effects. To investigate this possibility, a recent study showed words to participants while they were placed in one of two possible virtual environments: on Mars or underwater (Shin et al., 2020). After learning, participants retrieved the words while in the same or different environment as during learning. The study replicated the context-dependent memory effect, and found a greater effect for context-relevant words – those judged to be useful in their current environment. As participants were required to make judgments about the words' usefulness in the environment, it is not known if contemplating the relationship between objects and environment is necessary for this effect. This relationship is a potentially important moderator of context-dependent memory effects given that information consistent with current knowledge is oftentimes remembered better than is inconsistent information (van Kesteren et al., 2012). The saliency of this object-environment relationship is therefore worthy of further study.

In the work described above targeting differences in memory discrimination for targets and similar lures (Racsmány, 2021), the object and its corresponding background image was intentionally unrelated. Therefore, the question remains open as to whether objects which are semantically related would be even more difficult to distinguish if they had been seen before. This outcome is likely when one considers that such objects would typically be found in that context, making their appearance alongside the context during the study less surprising. Answers to this question could also speak to important distinctions relating to the fuzzy trace theory (Reyna et al., 2016) and whether people recognize general prototypes of an object (e.g., they had previously seen a spatula) or specific exemplars of that object type (e.g., plastic spatula with a red handle).

Providing additional meaning and increasing the associations within the semantic context has been shown to increase false alarms (Alakbarova et al., 2021). Similarity between the to-be-learned information and the context, therefore, would be expected to result in false alarms and difficulty discriminating between objects that had been previously seen before (or not).

1.4 Virtual Reality Methodology

In the pursuit of knowledge and better understanding of the way our cognitive systems work, we must remain vigilant to not lose sight of the usefulness of generalizability of our research.

Understanding how someone learns and remembers a set of objects is meaningful and impactful if we expect that it will extend to more desirable to-be-remembered items. Concerns about how our cognitive systems process real-life vs laboratory-based stimuli as part of memory research have been raised (for review, see Kvavilashvili & Ellis, 2004). Importantly, discrepancies have been observed in terms of the underlying mechanisms (Cabeza et al., 2004) and neural activity (Diamond et al., 2020) when comparing real-world and laboratory research.

The use of naturalistic videos has provided a promising lens through which to study memory, in a more ecologically valid manner. In both behavioral and neuroimaging research, such naturalistic videos provide opportunities to better understand our memory systems' responses to dynamic and high-dimensional factors (Coutanche et al., 2020; Koch et al., 2020). Additionally, it is important to consider how closely our experimental stimuli can reflect real-world nature, and how we can continue advancing this notion. For example, even when using natural human face stimuli, the addition of more naturalistic features such as hair and other facial accessories should be taken into account (Mannion et al., 2023).

One middle-ground particularly suited to addressing the gap between real-world and laboratory-based research is the realm of virtual reality (VR). Recently, studies investigating autobiographical memory (Schöne et al., 2019) as well as the role of self and perspective in episodic memory (Penaud et al., 2022) have benefitted from the introduction of VR methodology. VR provides an improved path forward by allowing us to more realistically interact with information. This can better inform us about how our memory systems naturally operate, compared to the use of traditional word lists or images.

VR technology has gained traction in recent years within the field of cognitive psychology as a useful way, in particular, to study episodic memory (Smith, 2019; Reggente, 2023). VR can provide numerous benefits to both the user, and the researcher wishing to use it to study a particular phenomenon. This technology can make prohibitive real-life tasks (e.g., due to safety, cost, etc.) more easily accessible within a virtual space. Stressful VR methods have been used to elicit psychological, as well as physiological stress responses (Martens et al., 2019). Learning in a virtual space has additionally been found to transfer to the real-world (e.g., learning spatial routes; Lloyd et al., 2009), making applicability even more attractive. Furthermore, as technology progresses, methodological and implementation limitations may be minimized.

Direct interaction with presented material is one particular area in which VR methodology can make experiments much more accessible than traditional laboratory-based studies. Instead of storing 30 household objects within a physical laboratory room, a study conducted virtually can store an incredibly large number of objects to be presented. Additionally, object manipulation and grasping can still be preserved through this approach, whereas it would be unrealistic using a traditional desktop computer and keyboard/mouse.

This is important because object manipulation and action affordance has key implications for representations of semantic memory (Lee, 2018; Yee, 2013). In fact, it has been suggested that the way in which we typically grasp an object should be considered as a part of our knowledge about that object (Martin, 2007). It is no surprise then, that recent work has found benefits to memory when participants grasped towards a projection of a to-be-learned object, compared to when they did not perform this grasping action (Macedonia et al., 2020).

Traditional research investigating context-dependent memory effects range in their use of contexts, such as the physical environments used in the earliest landmark studies (e.g., underwater or on land), to text and images presented in front of a participant on a computer screen.

While recent VR studies have provided evidence in support of context-dependent memory effects (Shin et al., 2020; Essoe et al., 2022), this is not always the case. Wälti and colleagues investigated potential differences in context-dependent memory effects when using a variety of contexts, such as traditional desktop background images, VR virtual backgrounds, and background flickering (Wälti et al., 2019). They only found support for a context-dependent memory effect in free recall when the background flickering was reinstated (no differences were observed when using the traditional or virtual backgrounds). Additionally, participants who learned and recalled words in the virtual environments recalled more overall than those participants in the traditional and flickering scenarios. The authors recommend caution in these findings, however, as a follow-up study failed to replicate these effects. In this follow-up study, no benefits were found when using either traditional backgrounds, virtual environments, or flickering backgrounds (this time within a head-mounted display). Furthermore, none of the three conditions differed from each other in terms of overall memory recall.

While VR remains an exciting and viable venue in which to pursue context-dependent memory, more work remains to be done to identify when context-dependent memory effects are most likely to occur, as is the case when using traditional *real-world* methodology.

1.5 Feelings of Immersion and Presence

A key component when considering VR methodology relates to the feelings of presence one may feel as a result of being immersed into various virtual environments (Smith, 2019). In general, feelings of immersion and presence have been investigated across a variety of studies utilizing VR methodology, often revealing benefits to memory when experiences are more immersive.

This has important implications for context-dependent memory effects because if a person does not feel that they are actually in a given environment, then we may be less likely to observe any effects of changing that environment (if they never felt like they were actually there to begin with). When employing VR methodology, feeling immersed in a distinct space seems to be key. This was apparent in a recent VR study investigating novel language learning (Essoe et al., 2022). Participants who indicated feeling more immersed (as evidenced by self-reported presence scores) in two distinct environments showed greater context-dependent memory effects than participants who felt less immersed. This led the researchers to conclude that the subjective experience one has within a context can be important for producing a context-dependent memory effect. If a person does not truly feel like they are in a certain environment, then it is less likely that that environment will serve as a retrieval cue later. This would then minimize (or eliminate) any effect that a change in the environment would have on their memory. Additionally, distinctive contexts can provide unique cues which become bonded to the to-be-remembered items from each context (Essoe et al., 2022). This coincides with theories described above suggesting that attention and awareness of the context are vital for observing context-dependent memory effects.

1.6 Aims

The present work, comprising immersive virtual reality studies, seeks to better understand the circumstances under which context-dependent memory is most beneficial. I specifically targeted the naturalistic components of the context in which participants learned and tested, as well as the relationship between the context and the to-be-learned material. Furthermore, I investigated both recall and recognition memory to determine if they were affected by context-dependent effects in the same or different ways.

Study 1 investigates which specific features are most likely to result in context-dependent memory effects: those relating to the relevance of the relationship of the object to the context (schema) and/or the context itself (e.g., the presence or absence of dynamic background components; the feelings of being in a given context (as represented by degree of immersion) when learning unique material. To accomplish this, I use two distinct virtual environments, more than 240 three-dimensional virtual objects, and both recall and recognition memory testing measures.

Study 2 extends the ideas of Study 1, while focusing on how interacting with the to-be-remembered objects impacts the context-dependent memory effect. I explore if recognition memory is affected by grasping and moving objects around during retrieval. To study this, I manipulate whether interacting with an object is required.

Furthermore, Study 3 expands on the methodological approach to studying context-dependent memory more broadly by recruiting participants from around the world (as opposed to only those who are able to participate in the local lab space). This study examines the benefits (and potential pitfalls) of implementing such an approach and evaluates its usefulness for future researchers wishing to employ similar methods.

2.0 Study 1: Identifying when context-dependent memory effects are likely to occur

Our memories are useful in our everyday lives. Seemingly without our awareness, we are able to remember what we encounter daily across varied environments: while driving to work, sitting in the office, or walking alongside a river.

The ‘context-dependent memory effect’ refers to when memories are more likely to be retrieved when the context of encoding matches that of retrieval (Smith & Vela, 2001). Though Godden and Baddeley’s (1975), as well as other work supported the context-dependent memory effect, this has not always been the case for ensuing studies. For example, testing in the same or different physical rooms using either pairs of related words (Experiment 3) or unrelated words (Experiments 1 and 2) printed on paper did not consistently result in context-dependent memory effects (Fernandez & Glenberg, 1985). More recently, researchers failed to find evidence supporting context-dependent memory effects using traditional desktop background images and, separately, VR virtual backgrounds (Wälti et al., 2019). Outside of the laboratory, beneficial context-dependent memory effects were only observed when skydivers learned word lists (unrelated to the context of the study) from an audio recording in low-arousal contexts (e.g., when not physically falling through the air) but not when learning and recall both occurred during skydiving (Thompson et al., 2001). Moderating factors have yet to be identified.

The encoding specificity principle (Tulving & Thomson, 1973) can help us make sense of how peripheral information can be helpful for remembering specific items. When tasked with remembering something, we attempt to draw on any information which was available at the time of encoding to help us. The information present during encoding in multiple contexts may differ dramatically, however, for example, in Godden and Baddeley’s study of land and underwater.

One feature that distinguishes the objects and contexts we encounter is their current relevance. A recent virtual reality (VR) study of context-dependent memory (Shin et al., 2020) had participants judge the usefulness of presented words to their current virtual environment –on Mars or underwater– and then retrieve these words in either environment. This study replicated context-dependent memory effects within VR, and found a greater context-dependent memory effect when the words were context-relevant (e.g., *net* when underwater) versus context-irrelevant (e.g., *net* on Mars). Another noteworthy feature of this study was its use of words within the VR environment. It is more common to encounter environmentally-relevant concepts in the form of physical objects, which are processed differently to remembered words (Hovhannisyan et al., 2021).

In addition to conceptual differences between physical objects and words, we can also consider how the movement of objects may impact how we visually process them, and eventually integrate them into memory or not. Stimuli in motion have been found to be remembered better than their static counterparts (Goldstein et al., 1982). Furthermore, prior work has suggested that the fluidity of the motion could be key for this memory benefit (Matthews et al., 2007). Sequences of multiple static images were found to be no better remembered than single static images, and neither were remembered as well as dynamic video clips. These findings suggest that object representations stored in memory do not just consist of spatial information for where the object was encoded, but also spatiotemporal features that may change throughout a dynamic episode (Matthews et al., 2007). It has been suggested that better feature integration, resulting from the presence of dynamic components, could be driving such memory benefits (Chung et al., 2022).

Particularly relevant for the current work, the notions of motion and memory have also been extended to comparisons between whether motion is present during encoding and/or retrieval. Memory performance was best when the encoding and retrieval phases matched in terms of presence of motion (Matthews et al., 2010). Similar findings have also been observed when participants remembered varied stimuli such as scenes (Buratto et al., 2009) and human faces (Butcher et al., 2011).

These behavioral findings are further supported by recent neuroimaging studies comparing neural activity when accessing memories for dynamic episodic memories compared to static representations. Researchers identified certain posterior medial brain regions, such as the precuneus, which elicited increased activity when retrieving memories for dynamic, compared to static, instances (Jeunehomme et al., 2022).

In addition to objects, another feature of interest is the complexity of background components, which also affect attention and visual processing of perceptually rich environments (Wang et al., 2021). Prior work has found context-dependent memory effects resulting for items learned in perceptually multimodal formats (e.g., using background movie clips (Smith & Manzano, 2010)). It is still yet to be determined whether these effects extend to dynamic components present within the periphery of a context, or whether they need to be more closely spatially located near the to-be-remembered information (such as being superimposed on top of them in Smith & Manzano, 2010).

Finally, within VR, the level of immersion felt in a context may affect context-dependent memory. If a person does not feel that they are actually present in a given environment, we are less likely to observe any effects of changing that environment (Essoe et al., 2022).

Here I present a large VR study that asks whether, and how, context-dependent object recall and recognition are affected by object/context relevance (schema) and the dynamic (versus static) nature of the context. Because the context-dependent memory effect is often only studied using free recall (Smith & Vela, 2001) rather than recognition (which can be moderated by different factors; Coutanche et al., 2020), here I study both within the same VR paradigm. I hypothesized that schema-relevant object/context pairings and dynamic contexts would each lead to stronger context-dependent memory effects in both recall and recognition.

2.1 Methods

2.1.1 Participants

Participants were recruited until 240 contributed usable data evenly across four conditions (exclusion criteria below). Participants were eligible if between 18 and 50 years old, fluent in English, having normal or corrected-to-normal vision, not currently having a cognitive disability (such as a learning or attention disorder), and being able to stand without interruptions for approximately 1 hour. While progressing to the 240-participant target, eight participants' data were not included due to likelihood of low effort or attention in the encoding and distractor tasks (e.g., accuracy scores more than three standard deviations below the mean of the entire group). Data for five objects (across four participants) were excluded due to a technical issue. One participants' audio recording during the free recall task was ended early, so they were excluded from any analyses involving free recall. The sample size for each condition was based on an a priori power analysis (power = 0.8) using parameters from Wälti et al. (Experiment 2; 2019) when matching contexts had a beneficial effect on free recall memory performance. To conduct the power analysis, first, I replicated their results using models analyzing the publicly available dataset. Then, I extracted the fixed and random effects, as well as error values and used these as the population parameters to estimate power for my own study. I conducted 100 simulated iterations (creating a new random sample for each iteration) to determine how often a statistically significant result (p $< .05$) would be observed in the simulations. I modified the sample size as necessary until arriving at a size that resulted in my goal power value of 0.8. This sample size target for each condition was also in line with a recent VR study investigating context-dependent memory (Shin et al., 2020). Upon completion of the tasks, participants were compensated for their time through either course credit or payment. See Table 1 for demographic information for all participants' data included in final analyses. The Institutional Review Board (IRB) approved all measures prior to data collection.

2.1.2 Procedure

All four conditions followed the same procedure, excepting the modifications to the environments described below. After eligibility screening and consent, participants started the session with a basic VR tutorial, which (along with the experimenter) provided guidance about how to move around and grasp objects in VR. The experimenter then exited the lab room, and the participant was placed into a virtual hallway environment where they began the VR experiment by reading instructions for the encoding task. A webcam and screen-sharing system allowed the experimenter to see both the participant and their virtual viewpoint, as well as to communicate if any issues or questions arose.

Table 1 Demographic information

Condition (encoding – recognition)	Age	Gender	First Experience in VR?
S-S	20.1 (4.3)	F: 32, M: 27, NB: 1	Yes: 26, No: 34
M-S	20.5 (5.2)	F: 37, M: 23, NB: 0	Yes: 23, No: 37
S-M	20.0 (2.5)	F: 34, M: 25, NB: 1	Yes: 25, No: 35
M-M	19.4 (1.7)	F: 37, M: 21, NB: 2	Yes: 25, No: 35

Note. Demographic information for analyzed participants. One of the virtual environments differed in background components being static (S) or containing motion (M) – within encoding or recognition (e.g., static during encoding, motion during recognition; S-M). Gender abbreviations: Female (F), Male (M), Non-binary (NB). *Non-binary* includes individuals identifying as non-binary or gender-fluid. Standard deviations in parentheses.

During each of the two encoding sessions, participants were introduced to a set of 30 individual objects (details below) that are typically found in one of the environments (e.g., spatula for kitchen; globe for classroom) or neither (e.g., bicycle). Participants were introduced to the objects without explicitly drawing attention to any type of relationship with the environment, nor told of any future memory tasks. Participants incidentally encoded the objects through a value-based sorting task. Each object individually appeared on a virtual countertop (kitchen) or desk (classroom) and was picked-up and moved by participants into one of two virtual boxes labeled “More than $20” or “Less than $20”. After sorting the object, participants returned to the countertop or desk for the next object. After sorting all 30 objects in one environment, participants were relocated to a new virtual environment to sort a new set of 30 objects. This procedure ensured that participants interacted with the objects both physically (by picking them up and placing them) and semantically (by categorizing based on perceived cost). On average, participants spent 6.8 (Standard Deviation (*SD*) =1.8) minutes completing both of these encoding sessions.

After the two encoding sessions, participants completed a five-minute distractor task of vocabulary and math questions, in the same hallway environment where they first started the experiment. Using either hand[1], participants selected the closest synonym (for vocabulary questions) or numerical answer (for math questions) from a set of three choices in text boxes. After five minutes of the distractor task, participants were relocated to one of the two earlier encoding environments (specific environment counterbalanced across participants) to perform a free recall test in which they were instructed to "describe out loud as many of the objects you had categorized into the boxes earlier as you can remember". If a participant asked for clarification or indicated that they were only recalling objects from only one of the encoding environments, researchers verbally informed them to recall from both. On average, participants spent 2.4 (*SD* = 1.4) minutes attempting to recall objects.

Next, participants were relocated to the other (counterbalanced) encoding environment for testing recognition memory based on the Mnemonic Similarity Task (Stark et al., 2013). In this test, an object appeared in the same location as during encoding. These objects were either previously presented in one of the environments ("old"), a different exemplar of a previously presented object ("similar"), or a type of object not previously seen in the experiment ("new"). Participants used their hand or the object to touch a label indicating "old", "similar" or "new". Participants were instructed that they could grab and pick up the objects if that would help them

[1] One participant recently injured their wrist prior to participation and therefore only used one hand (and controller) for all VR tasks.

make their decision. On average, participants spent 11.4 (*SD* = 2.4) minutes completing the recognition memory test.

Finally, participants were removed from VR and completed a survey about demographics, VR experience, feelings of presence within each virtual environment (e.g., “Please rate your sense of being in the kitchen, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place”; adapted from Usoh et al., 2000), and the likelihood of finding each object in a typical kitchen or classroom. The entirety of the study (including VR and non-VR sessions) lasted approximately 1 hour.

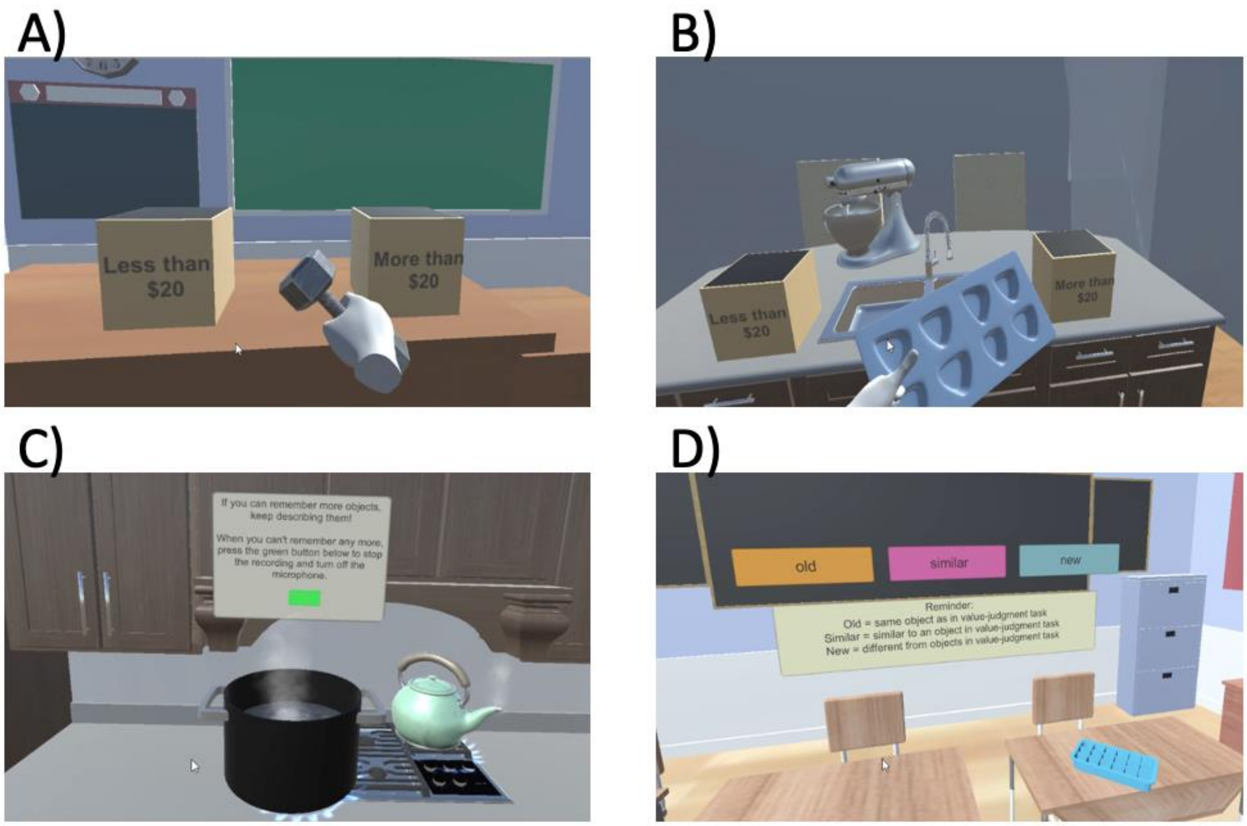

Figure 1 A and B: Screenshots from the sorting task in each virtual encoding environment. C: Free recall task. D: Recognition task within one of the environments, where participants selected “old”, “similar” or “new”.

2.1.3 Materials

During initial instructions, distractor task, and ending instructions, participants were placed into a virtual hallway with few background features. The encoding and retrieval tasks, two virtual environments were used: a classroom and a kitchen. The classroom environment consisted of background items such as desks, chairs, a bookshelf, windows with curtains, a blackboard, a clock, etc. The kitchen environment consisted of kitchen cabinets, chairs, windows and curtains, sink, kitchen appliances, tea kettle and pot of water on the stove, stand mixer, and a clock. For the static-only condition, all background objects were unchanging. For motion conditions, the kitchen background objects were made dynamic: curtains blowing in the wind, spinning electric-mixer, steaming tea kettle, boiling pot of water on the stove, rotating clock hands, and running sink faucet.

A previous norming study (See Appendix A) guided us in selecting 40 kitchen objects expected to be found in a kitchen, 40 classroom objects expected to be found in a classroom, and an additional 40 miscellaneous objects that are not expected in either environment. Ratings from participants in a post-VR survey confirmed my selection of objects (see Table 2). An additional 120 exemplars of the same type of object served as lures during the recognition memory test. Each lure's orientation matched its associated target object. Each participant saw a random subset of objects (10 from each object schema in each environment for a total of 60 encoded objects), counterbalanced as target or lure.

Table 2 Object Schema Ratings

Object schema	Kitchen rating	Classroom rating
Kitchen	6.6 (0.4)	1.3 (0.2)
Classroom	1.9 (0.6)	6.3 (0.5)
Miscellaneous	1.4 (0.3)	1.8 (0.5)

Note. Object schema ratings from analyzed participants on a 7-point scale of where an object would typically be found (1 = not very likely, 7 = very likely). Standard deviations shown in parentheses.

2.1.4 Free Recall Scoring

Audio recordings of the free recall were first transcribed using Microsoft's *Transcribe* feature and confirmed by a human researcher. Then, two independent coders separately identified the objects described in the recordings (90% consistency) with discrepancies settled by a third independent coder.

2.1.5 Hardware

All VR tasks were completed by participants in a laboratory while wearing an Oculus Rift S head-mounted display connected to either an HP Pavilion Gaming Desktop running Windows 11 Home, or an Alienware m15 laptop running Windows 10 Home. A custom hardware pulley set-up prevented the headset's cable from interrupting participants during the tasks. VR tasks were coded with the UXF framework (Brookes et al., 2020) within Unity (version 2018.3.14). Virtual environments and objects were downloaded from the Unity Asset store (https://assetstore.unity.com/) or Sketchfab (https://sketchfab.com/) and modified within Unity to cohesively match (e.g., realistic size) within the environments.

2.1.6 Statistical Analyses

To analyze memory performance data, I conducted separate logistic mixed-effects regression models (Baayen et al., 2008). For memory recall, I predicted whether a participant recalled an object they had seen before. For memory recognition, I conducted three separate models to individually investigate hits, lure discrimination, and false alarms (following the approach used by Racsmány et al., 2021), unless otherwise noted. I controlled for the presence of background motion by using separate fixed effects terms for encoding and retrieval. When investigating participants' ratings of presence, I used the average rating from the six questions of the presence questionnaire, for each environment. To investigate the effect of motion, I used orthogonal contrast coding between four possible conditions. I compared 1) environments containing no motion versus motion, 2) environments containing motion during both encoding and retrieval versus motion during only one, and 3) environments containing motion only during encoding vs motion only during retrieval. Each regression model included random effects for participant and object. For ease of interpretation, figures depict averages at the participant level.

2.2 Results

2.2.1 Memory Recall

I examined the context-dependent memory effect for objects learned within two separate virtual environments. I also investigated how schema affects context-dependent memory. Nearly all participants (96%) recalled at least one object from each of the two environments. None of the remaining participants indicated that they were purposefully recalling from only one environment.

I found evidence supporting the context-dependent memory effect ($\beta = 0.16$, $SE = 0.05$, $Z = 3.39$, $p < .001$), such that objects were more likely to be freely recalled in the same environment as encoding ($M = 0.22$, $SD = 0.11$) than in the other environment ($M = 0.20$, $SD = 0.12$).

Examining overall recall (without considering whether encoding and retrieval contexts match), objects that were schema-relevant with the encoding environment (e.g., learned spatula in kitchen) were no more likely to be freely recalled than schema-irrelevant objects (e.g., pencil sharpener in kitchen; $\beta = 0.03$, $SE = 0.05$, $Z = 0.49$, $p = .624$). Schema relevance with the encoding environment interacted with the context-dependent memory effect ($\beta = 0.21$, $SE = 0.09$, $Z = 2.27$, $p = .023$), such that the context-dependent memory effect was observed for schema-relevant objects ($\beta = 0.25$, $SE = 0.07$, $Z = 3.33$, $p < .001$), and not schema-irrelevant objects ($\beta = 0.05$, $SE = 0.05$, $Z = 0.90$, $p = .367$), see Figure 2. I next added to the model a fixed effect term representing participants' ratings of presence in the corresponding encoding environment. This resulted in a better model fit (Δ AIC = -4, $\chi^2(1) = 5.91$, $p = .015$), such that every one point increase in feeling of presence increased the odds of recall by 1.08 times. Lastly, I investigated whether differences in motion within the encoding environment affected free recall performance. I restricted this analysis to only those objects encoded within the kitchen, as that was the only environment which could either contain static or motion. Free recall performance did not differ for any of my three motion comparisons: static vs motion (β = -0.06, *SE* = 0.11, *Z* = -0.57, *p* = .572), motion during both encoding and recall vs motion during only one (β = -0.29, *SE* = 0.21, *Z* = -1.36, *p* = .175), motion during only encoding vs motion during only recall (β = -0.12, *SE* = 0.16, *Z* = -0.76, *p* = .446).

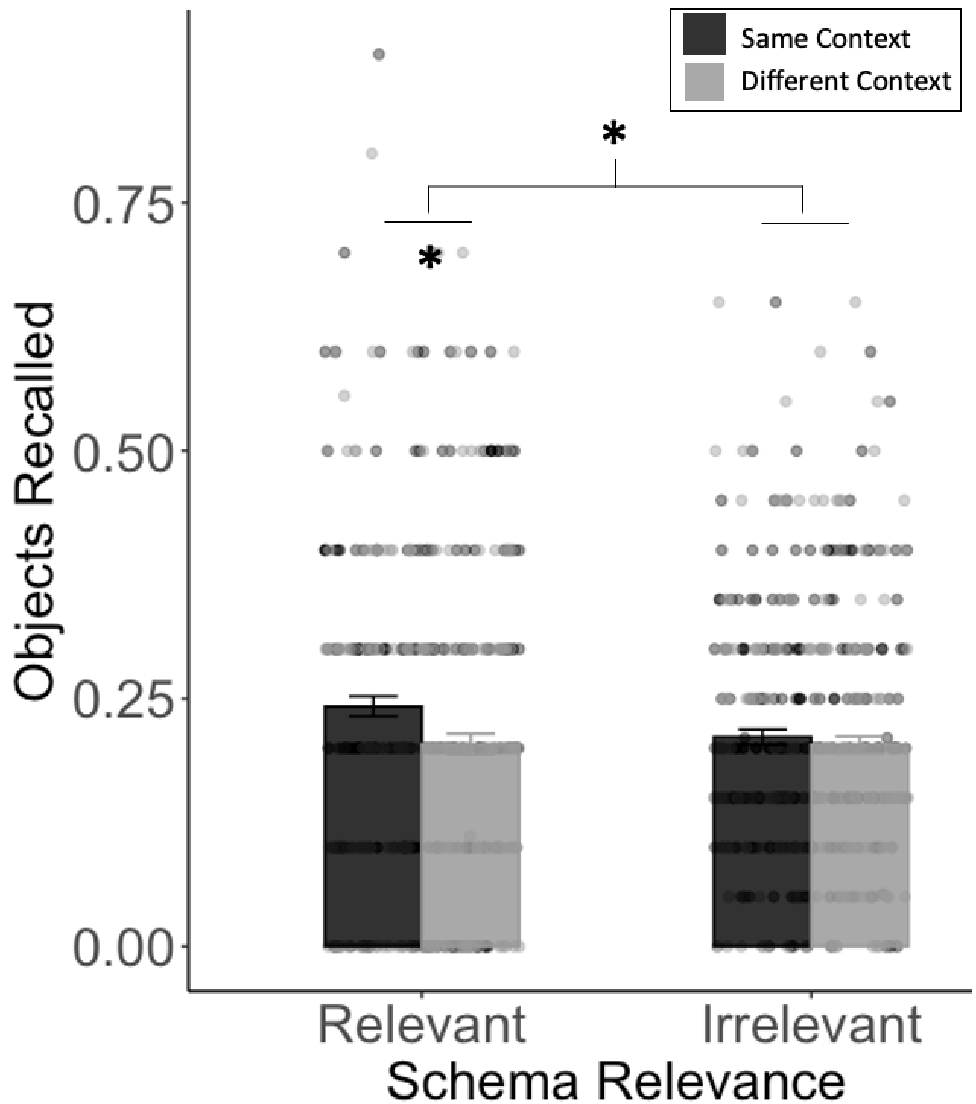

Figure 2 Average ratio of objects recalled when encoding and retrieval environments are the same or different, and objects were relevant (or irrelevant) with their encoding environment. Error bars represent SEM. * represents *p* < .05.

2.2.2 Memory Recognition

Having examined memory recall, I next investigated memory recognition. My design allowed us to investigate the specificity of participants' memory by testing participants' ability to recognize objects that were old, similar (to previously seen items) or new.

First, I investigated differences in hit rate (correctly identifying an object as seen before), which showed marginal support trending towards statistical significance for the context-dependent memory effect ($\beta = 0.09$, $SE = 0.05$, $Z = 1.82$, $p = .069$), with a slightly greater hit rate for matching ($M = 0.84$, $SD = 0.10$) than non-matching ($M = 0.83$, $SD = 0.12$) encoding/retrieval contexts, see Figure 3. Schema relevance with the encoding environment did not affect hit rate ($\beta = -0.08$, $SE = 0.06$, $Z = -1.39$, $p = .165$), nor interact with the context-dependent memory effect ($\beta = -0.16$, $SE = 0.10$, $Z = -1.62$, $p = .106$). Adding presence to the model did not increase the fit for predicting hit rate (Δ AIC = 2, $\chi^2(1) = 0.07$, $p = .793$).

There also were not differences in hit rate for any of my three motion comparisons for objects encoded in the kitchen: static vs motion ($\beta = -0.10$, $SE = 0.12$, $Z = -0.79$, $p = .428$), motion during both encoding and recall vs motion during only one ($\beta = -0.05$, $SE = 0.25$, $Z = -0.20$, $p = .838$), motion during only encoding vs motion during only recall ($\beta = 0.04$, $SE = 0.19$, $Z = 0.22$, $p = .828$).

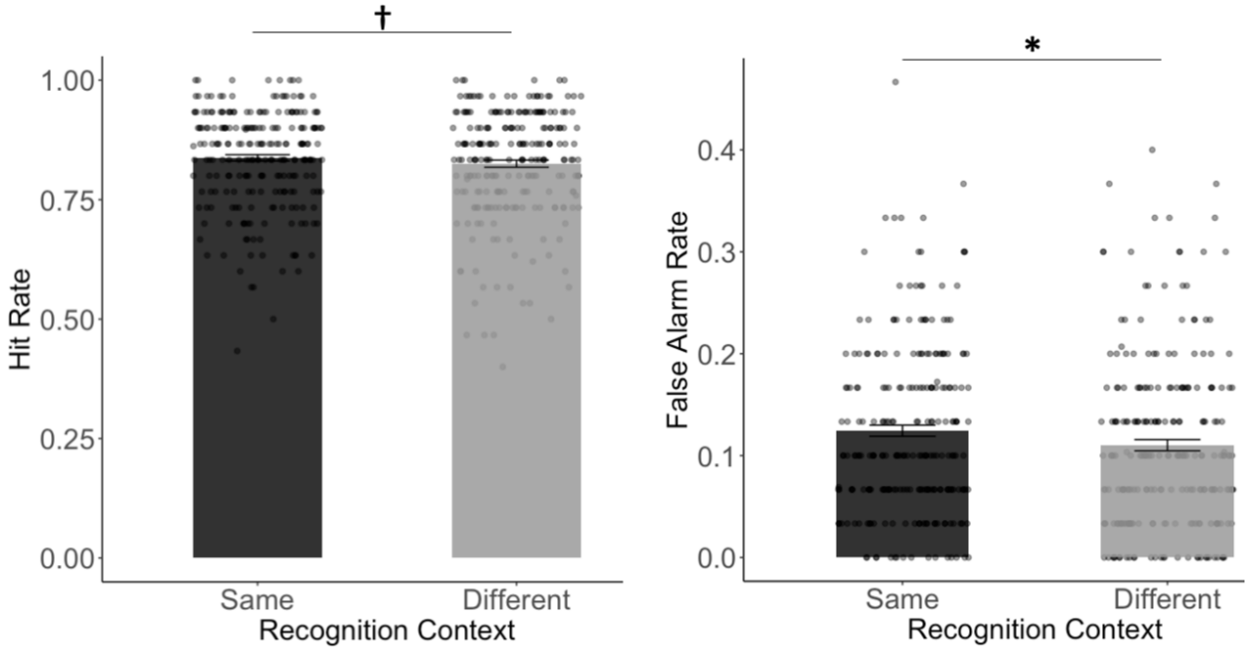

Figure 3 Average hit rate (correctly indicating an "old" object as "old"; left) and false alarm rate (incorrectly indicating a "similar" object as "old"; right) for same/different encoding and retrieval environments. Error bars represent SEM. * represents *p* < .05; † represents *p* < .1

Moving beyond simple recognition, I next investigated the ability to discriminate similar lures from previously seen objects (following the approach outlined in Racsmány et al., 2021). Successfully identifying objects as 'similar' (i.e., lure discrimination) was not affected by the corresponding old objects having matching or mismatching encoding and retrieval environments ($\beta = -0.05$, $SE = 0.05$, $Z = -1.12$, $p = 0.261$). Participants were better at identifying similar objects as 'similar' (rather than old or new) for objects irrelevant to the encoding environment ($M = 0.77$, $SD = 0.12$) than relevant objects ($M = 0.72$, $SD = 0.14$; $\beta = -0.08$, $SE = 0.05$, $Z = -1.65$, $p = 0.099$) at a trending level. Schema relevance with the encoding environment did not interact with the match between encoding/retrieval environments ($\beta = -0.08$, $SE = 0.09$, $Z = -0.90$, $p = .370$). To better understand the effect of schema relevance, I ran a continuous model using each object's average rating of how likely it was to be found in the encoding environment (relating to Table 2).

Continuous ratings were centered at the participant level prior to being included in the model. Ratings for schema relevance with the encoding environment did not scale with the ability to correctly identify similar objects as *similar* (β = -0.01, *SE* = 0.01, *Z* = -1.37, *p* = .172).

As with hit rate, presence did not increase the fit for predicting mnemonic discrimination (Δ AIC = 1, $\chi^2(1) = 0.60$, *p* = .439).

Participants experiencing only static environments (*M* = 0.78, *SD* = 0.13) performed better than participants who experienced motion during some point in the study (*M* = 0.73, *SD* = 0.13; β = -0.27, *SE* = 0.12, *Z* = -2.30, *p* = .022). Additionally, participants who experienced motion during both encoding and recognition (*M* = 0.77, *SD* = 0.14) performed better than participants who experienced it during only encoding or recognition (*M* = 0.73, *SD* = 0.13; β = 0.42, *SE* = 0.23, *Z* = 1.78, *p* = .075) at a trending level. Participants did not differ if they experienced motion during encoding compared to during recognition (β = -0.04, *SE* = 0.17, *Z* = -0.23, *p* = .817).

Lastly, I investigated false-alarm rate for identifying similar objects as old. False alarm rates were higher when the recognition environment matched the encoding environment of the old object used to generate the lure (*M* = 0.12, *SD* = 0.08) than when they did not (*M* = 0.11, *SD* = 0.08; β = 0.17, *SE* = 0.06, *Z* = 2.67, *p* = 0.008), see Figure 3. Put another way, reinstatement of a context led participants to over-generalize recognition to a similar (but actually new) object. False alarm rates were not affected by schema relevance with the old objects' encoding environments (β = 0.02, *SE* = 0.07, *Z* = 0.22, *p* = .829), nor interacted with the match between encoding/retrieval environments (β = 0.10, *SE* = 0.12, *Z* = 0.80, *p* = .426). Presence did not affect false alarm rate (Δ AIC = 1.6, $\chi^2(1) = 0.38$, *p* = .537). Participants who experienced motion made more false alarm judgments (*M* = 0.12, *SD* = 0.08) than those who only experienced static environments (*M* = 0.10, *SD* = 0.08; β = 0.29, *SE* = 0.14, *Z* = 2.11, *p* = .035). False alarm rates did not differ between participants who experienced motion during both encoding/recognition vs only one ($\beta = -0.36$, $SE = 0.28$, $Z = -1.31$, $p = .192$), nor between those who experienced them during only encoding compared to only recognition ($\beta = 0.12$, $SE = 0.21$, $Z = 0.57$, $p = .566$).

2.2.3 Specificity of Memory Recall

Our design allowed us to investigate the specificity of the recalled objects in memory by asking how well free recalled objects were discriminated from their lures (while keeping successful recognition constant) . Of the full set of objects that each participant correctly recognized as 'old', those that had been free recalled were significantly better discriminated ($\beta = 0.48$, $SE = 0.07$, $Z = 6.88$, $p < .001$) from their similar lures ('similar' hit rate: $M = 0.84$, $SD = 0.16$) than were non-free-recalled recognized objects ('similar' hit rate: $M = 0.78$, $SD = 0.12$).

2.3 Discussion

Here I provide evidence of context-dependent memory effects in two forms of memory retrieval: recall and recognition. My studies provide a more detailed understanding of context-dependent memory effects, and particularly identify when the object-context relationship is advantageous for memory.

After replicating the context-dependent memory effect for objects in VR, I found that this effect interacted with the object's relevance with the spatial context of encoding. Specifically, the context-dependent memory effect in free recall only existed for those objects that were encoded in a schema-relevant context, but not in a schema-irrelevant context. This finding suggests that not only is the item-context relationship important (Shin et al., 2020), but that this relationship does not need to be explicitly processed by the person (i.e., is automatically processed). This is important because it suggests that people semantically integrate items into their encoding context (giving a future benefit to recall) without needing to be instructed to do so (e.g., as employed in Shin et al., 2020). This is also consistent with a prior finding that when explicitly directed to study faces and their contexts, participants have better memory for both the contexts and items (Hanczakowski et al., 2015). My work provides evidence that the beneficial semantic integration of an item with its context does not require explicit directions.

Our finding can also potentially address why some prior work has failed to replicate the context-dependent memory effect. For example, Wälti and colleagues failed to find the context-dependent memory effect using either immersive VR or traditional desktop computer presentation methods (Wälti et al., 2019). Their to-be-learned words, however, were deliberately chosen to not contain "obvious connections to one of the visual contexts" (p. 4). It is plausible then, that their words were not semantically integrated with the context during encoding, eliminating the benefits that I have shown here.

The above findings are consistent with prior work showing that similar (rather than identical) retrieval contexts can give the context-dependent memory effect (Hockley, 2008), which could be explained by learners associating to-be-remembered items with the schema of the encoding context, rather than highly specific features of the context.

In addition, I present mixed findings on the role of motion (a form of increased contextual richness) on context-dependent memory. While I hypothesized that the presence of motion would enhance memory performance, this was not entirely the case. There was only a marginal benefit to mnemonic discrimination of lures when both encoding and retrieval contexts featured motion.

Additionally, participants who experienced both environments in strictly static conditions performed better on mnemonic discrimination and made fewer false alarms than participants who experienced motion at some point during the study. One explanation for this null result is that the motion present in the background was not salient enough for participants to be affected by its presence. Motion within background videos (e.g., successfully used in Smith & Manzano, 2010) is more noticeable compared to an environment's background components.

I also found evidence that free recall draws on not just the general gist of an object, but rather includes features that discriminate the freely recalled item from others of the same object-type (here, similar lures). This result cannot merely be explained by differences in memory strength, as the corresponding objects (from which the lures had been drawn) in this analysis had all had been correctly identified as old.

Our work sheds light on some mixed findings in prior literature. The context-dependent memory effect has more often been found in free recall memory tests (Smith & Vela, 2001). I build upon prior findings by Racsmány et al. (2021) in showing that contexts can be both helpful, and harmful, for memory. While retrieving in encoding context was beneficial for recalling objects, it also led to a disadvantageous increase in false alarms during recognition. This suggests that people may over-generalize their recognition memory to unseen exemplars of the same object-type. The matching context may introduce a false sense of familiarity, leading to worse detection of subtle differences in items. When the retrieval context differs from encoding, fewer contextual cues are available, requiring us to rely only on our knowledge to correctly recognize the object.

This work continues an exciting avenue of using immersive and realistic settings (Smith, 2019) to better learn about human behavior and cognition.

3.0 Study 2: Grasping as a potential aid for Recognition Memory

If someone asks which color ink we used to sign an important document, our memory might not improve if we look down and see both a red and black pen sitting on our desk. But if we can't quite remember which pen we used, is there anything else we can do to help? If, after picking up one of the pens, might we be more likely to remember that we indeed used the black pen and not the red one? While we may readily associate shapes and colors with certain objects, previous research has suggested that the ways in which we grasp or interact with objects should be considered as part of a person's knowledge of an object (Martin, 2007). If these aspects of objects constitute a form of semantic knowledge of an object, how are they represented in memory? Do we readily draw on this information just from seeing it? Or do we have to be prompted to think about how we might pick it up or interact with it?

While research continues to probe answers to these questions, memory researchers have focused on the ways in which grasping and, potentially the sense of touch, can help us remember. One reason for such a benefit to memory relates to the concept of embodied cognition, how cognition is influenced by the body (Ianì, 2019). We see this influence when people's memories are improved for activities that have been physically performed compared to simply described (Earles, 1996). Such performed activities are also more difficult to intentionally forget (Earles & Kersten, 2002). Memory can therefore be impacted both by mental *and* physical actions. Importantly, congruency between the body and the semantic nature of a memory are important for retrieval. Prior work has demonstrated the increased ease of accessing autobiographical memories when one's body is positioned in a way that is congruent with how the memory may have been initially formed (Dijkstra et al., 2007). For example, lying down in a chair when retrieving a memory of a trip to the dentist would result in more successful memory retrieval than miming playing tennis and attempting to retrieve the same memory.

This connection between the body and memory ability can then be extended further when considering how the body typically interacts with or uses an object. There appears to be a particular bond between the ability to grasp an object and subsequent memory for the object (Dutriaux & Gyselinck, 2016). This notion was demonstrated in a study investigating differences in memory resulting from changes in posture during encoding. Participants saw pictures of objects that could be manipulated (or not) while their hands were either placed in front of them on a desk, or restricted from moving by being held behind them. Importantly, memory differences were only observed between the hand placement conditions for the manipulable objects, and not for those objects which could not be manipulated. Participants recalled fewer manipulable objects when their hands were restricted as compared to when they were free (and simply at rest in front of them).

This suggests that merely the *potential* for grasping and manipulation, rather than requiring the act of using an object, might underlie memory effects for manipulable objects. Real-world objects are remembered (recalled and recognized) better than matched photographs of those same objects (Snow et al., 2014), and words are better remembered when concrete (versus abstract; Fliessbach et al., 2006) and representing highly-manipulable items (Madan & Singhal, 2012). Interestingly, low-manipulable words are remembered better when participants are directed to attend to the potential actions and uses of a word, suggesting an important role for attention with respect to motor involvement in semantic memory processing.

Recent virtual reality (VR) experiments have extended our understanding of when context-dependent memory effects are most likely to be observed (Shin et al., 2020) or not (Wälti et al., 2019). Neither of these studies, however, speak to how newly learned virtual *objects* are represented in our memory systems, because they only investigated words. For example, Shin and colleagues (2020) required participants to explore and interact with their virtual environments through various movements and actions, to reveal a to-be-remembered word. Participants, therefore, needed to access the concepts and knowledge of a given item in a way that did not draw on its visual features (i.e., just the word-form). A recent study of language learning in VR used virtual objects representing to-be-learned concepts (Essoe et al., 2022), though participants were not able to manipulate or grasp these objects, and instead were instructed to “click” on them to advance to another object. Recently, Macedonia and colleagues demonstrated that second-language vocabulary words, learned in conjunction with grasping toward the outline of a (flat) visual projection of the associated object, were recognized faster than without this grasping action (2020).

Here, I ask whether grasping an object benefits memory recognition, while requiring participants to grasp and move virtual objects within a VR environment. My design incorporates virtual three-dimensional objects, as well as direct object manipulation (and therefore direct visual feedback) in response to participants’ motor actions. I also ask how the context-dependent memory effect is affected by grasping, and whether this interacts with the object and context belonging to the same schema. My VR study utilizes two virtual environments and objects that would typically be found in either (or neither) environment. I systematically controlled when participants could grasp an object or only observe it while making recognition memory judgments. I hypothesized that memory would be improved when grasping and moving (compared to just pointing at) objects, and that this benefit would be greater when encoding/retrieval contexts matched. I reasoned that this interaction benefit would be driven by stronger reactivation of the object knowledge in the same context as initial encoding. Furthermore, I predicted that the beneficial grasping effect would be even greater for schema-relevant object-context relationships as these are the instances when grasping would be the most natural and likely. Additionally, I expected that grasping would increase lure discrimination and minimize false alarms, due to the strengthened memory representations activated by the grasping and motor actions.

3.1 Methods

3.1.1 Participants

Participants were recruited until 60 contributed usable data. Participants met inclusion criteria of being between 18 and 50 years old, fluent in English, having normal or corrected-to-normal vision, not currently having a cognitive disability (such as a learning or attention disorder), and being able to stand without interruptions for approximately 1 hour. While progressing to the 60-participant target, one participant's data were not included due to likelihood of low effort or attention in the encoding and distractor tasks (accuracy scores more than three standard deviations below the mean of the entire group). The sample size was based on an a priori power analysis (power = 0.8) using parameters from Wälti et al. (Experiment 2; 2019) when matching contexts had a beneficial effect on free recall memory performance, following the procedure outlined in Study 1. This sample size target was also in line with a recent VR study investigating context-dependent memory (Shin et al., 2020). Upon completion of the tasks, participants were compensated for their time through either course credit or payment. Participants (*M* Age = 20.3 years, *SD* = 3.9 years) whose data were included in final analyses self-identified as female (*n* = 39), male (*n* = 20), and non-binary (*n* = 1). It was the first experience in VR for 25 participants, while 35 participants had prior VR experience. The Institutional Review Board (IRB) approved all measures prior to data collection.

3.1.2 Procedure

All tasks followed the same procedures as Study 1, except where described below. After eligibility screening and consent, participants started the session with a basic VR tutorial, which (along with the experimenter) provided guidance about how to move around and grasp objects in VR. In contrast to Study 1, during recognition, participants were additionally instructed to grasp half of the objects as they naturally would in real-life (e.g., to grasp the kitchen knife by the handle, not the blade). In Study 1, participants could only grab each object by an invisible "grab-point" at the center of the base of the object. For this study, I added widespread grab-points across the objects to make naturally grasping them easier.

During each of the two encoding sessions, participants were introduced to a set of 30 individual objects (details below) that are typically found in one of the environments (e.g., spatula for kitchen; globe for classroom) or neither (e.g., bicycle). Participants were introduced to the objects without explicitly drawing attention to any type of relationship with the environment, nor told of any future memory tasks. Participants incidentally encoded the objects through a value-based sorting task. Each object individually appeared on a virtual countertop (kitchen) or desk (classroom) and was picked-up and moved by participants into one of two virtual boxes labeled "More than $20" or "Less than $20". After sorting the object, participants returned to the countertop or desk for the next object. After sorting all 30 objects in one environment, participants were relocated to a new virtual environment to sort a new set of 30 objects. This procedure ensured that participants interacted with the objects both physically (by picking them up and placing them) and semantically (by categorizing based on perceived cost). On average, participants spent 6.5 (Standard Deviation (*SD*) =1.8) minutes completing both of the encoding sessions.

After the two encoding sessions, participants completed a five-minute distractor task of vocabulary and math questions, in the same hallway environment where they first started the experiment. Using either hand, participants selected the closest synonym (for vocabulary questions) or numerical answer (for math questions) from a set of three choices in text boxes.

After five minutes of the distractor task, participants were relocated to one of the two earlier encoding environments (specific environment counterbalanced across participants) to perform a free recall test in which they were instructed to "describe out loud as many of the objects you had categorized into the boxes earlier as you can remember". On average, participants spent 2.9 (*SD* = 2.2) minutes attempting to recall objects.

Next, participants were relocated to the other (counterbalanced) encoding environment for testing recognition memory based on the Mnemonic Similarity Task (Stark et al., 2013). In this test, an object appeared in the same location as during encoding. These objects were either previously presented in one of the environments ("old"), a different exemplar of a previously presented object ("similar"), or a type of object not previously seen in the experiment ("new").

As part of my key manipulation, participants were required to pick up half the objects and use them to indicate their "old", "similar" or "new" judgment, or point (to the other half of the objects) with their virtual hand to indicate their judgment (and were unable to pick up the object even if they attempted to). Moving the objects/pointing trials were completed in 4 blocks of 45 trials (all trials within a block were the same format). I counterbalanced the order in which participants completed the blocks (e.g., move the object-point-move the object-point or point-move the object-point-move the object). Additionally, matched *old* and *similar* objects were presented in the same format in separate blocks (e.g., *old* calculator needed to be picked up and moved in block 1; *similar* calculator needed to be picked up and moved in block 3). On average, participants spent 12.2 (*SD* = 2.3) minutes completing the recognition memory test.

Finally, participants were removed from VR and completed a survey about demographics, VR experience, feelings of presence within each virtual environment (e.g., "Please rate your sense of being in the kitchen, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place"; adapted from Usoh et al., 2000), and the likelihood of finding each object in a typical kitchen or classroom. The entirety of the study (including VR and non-VR sessions) lasted approximately 1 hour.

3.1.3 Materials

During initial instructions, distractor task, and ending instructions, participants were placed into a virtual hallway with few background features. For the encoding and retrieval tasks, two virtual environments were used: a classroom and a kitchen. The classroom environment consisted of background items such as desks, chairs, a bookshelf, windows with curtains, a blackboard, a clock, etc. The kitchen environment consisted of kitchen cabinets, chairs, windows and curtains, sink, kitchen appliances, tea kettle and pot of water on the stove, stand mixer, and a clock.

I used the same kitchen, classroom, and miscellaneous objects from Study 1, with slight modifications to the number of grab-points available (as described above). I used 40 kitchen objects expected to be found in a kitchen, 40 classroom objects expected to be found in a classroom, and an additional 40 miscellaneous objects that are not expected in either environment. Ratings from participants in a post-VR survey confirmed my selection of objects (see Table 3). An additional 120 exemplars of the same type of object served as lures during the recognition memory test. Each lure's orientation matched its associated target object. Each participant saw a random subset of objects (10 from each object schema in each environment for a total of 60 encoded objects), counterbalanced as target or lure.

Table 3 Object Schema Ratings

Object schema	Kitchen rating	Classroom rating
Kitchen	6.7 (0.9)	1.2 (0.5)
Classroom	1.9 (1.4)	6.4 (1.1)
Miscellaneous	1.4 (0.9)	1.9 (1.3)

Note. Object schema ratings from analyzed participants on a 7-point scale of where an object would typically be found (1 = not very likely, 7 = very likely). Standard deviations shown in parentheses.

3.1.4 Free Recall Scoring

Audio recordings of the free recall were first transcribed using Microsoft's *Transcribe* feature and confirmed by a human researcher. Two independent coders separately identified the objects described in the recordings (84% consistency) with discrepancies settled by a third independent coder.

3.1.5 Hardware

All VR tasks were completed by participants in a laboratory while wearing an Oculus Rift S head-mounted display connected to an HP Pavilion Gaming Desktop running Windows 11 Home. A custom hardware pulley set-up prevented the headset's cable from interrupting participants during the tasks. VR tasks were coded with the UXF framework (Brookes et al., 2020) within Unity (version 2018.3.14). Virtual environments and objects were downloaded from the Unity Asset store (https://assetstore.unity.com/) or Sketchfab (https://sketchfab.com/) and modified within Unity to cohesively match (e.g., realistic size) within the environments.

3.1.6 Statistical Analyses

To analyze memory performance data, I conducted separate logistic mixed-effects regression models (Baayen et al., 2008). For memory recall, I predicted whether a participant recalled an object they had seen before or not. For memory recognition, I conducted three separate models to individually investigate hits, lure discrimination, and false alarms (following the approach used by Racsmány et al., 2021), unless otherwise noted. When investigating participants' ratings of presence, I used the average rating from the six questions of the presence questionnaire, for each environment. Each regression model also included random effects for participant and object.

3.2 Results

3.2.1 Default Grasping Behavior

This study follows up the work previously presented in Study 1. The key difference between Study 1 and 2 occurred during the recognition trials. In Study 1, participants chose to either point or grasp and move the object to indicate their memory judgment response. In Study 2, rather than allowing participants to choose their behavior on each trial, I systematically controlled these options. Participants were required to grasp and move the objects for half of the recognition trials and point (without moving the objects) for the other half (more details above). When given the choice in Study 1, participants were more likely to point (M = 73.9% of trials, SD = 34.9%) to make their judgment as opposed to grasping (and moving) the object (M = 26.1% of trials, SD = 34.9%; $\beta = -1.99$, $SE = 0.30$, $Z = -6.69$, $p < .001$). Additionally, participants spent more time on the trials when they grasped and moved the objects (M = 6.60 s, SD = 2.80 s) compared to when they pointed (M = 2.30 s, SD = 1.71 s; $\beta = 4.28$, $SE = 0.04$, $t = 107.03$, $p < .001$).

3.2.2 Memory Recall

I examined the context-dependent memory effect for objects learned within two separate virtual environments. I also investigated how schema affects context-dependent memory. I found evidence marginally supporting the context-dependent memory effect ($\beta = 0.16$, $SE = 0.09$, $Z = 1.84$, $p = .066$), such that objects were more likely to be freely recalled in the same environment as encoding ($M = 0.25$, $SD = 0.13$) than in the other environment ($M = 0.23$, $SD = 0.14$). Schema relevance did not impact overall recall performance ($\beta = 0.05$, $SE = 0.10$, $Z = 0.53$, $p = .597$), and did not interact with the context-dependent memory effect (β = -0.05, SE = 0.18, Z = -0.30, p = .766). I next added to the model a fixed effect term representing participants' ratings of presence in the corresponding encoding environment. This did not result in a better model fit (Δ AIC = 2, $\chi^2(1)$ = 0.05, p = .815), suggesting no significant relationship between feeling of presence and recall performance.

3.2.3 Memory Recognition

Having examined memory recall, I next investigated memory recognition. My design allowed us to investigate the specificity of participants' memory by testing participants' ability to recognize objects that were old, similar (to previously seen items) or new. Additionally, I could also investigate the effect of motor action (i.e., grasping and manipulating an object or not) when making a recognition memory judgment.

First, I investigated differences in hit rate (correctly identifying an object as seen before), but did not observe the context-dependent memory effect (β = 0.14, SE = 0.10, Z = 1.40, p = .160), nor an effect of schema relevance (β = -0.14, SE = 0.11, Z = -1.31, p = .189). My key variable of interest, motor action, also did not predict hit rate (β = -0.11, SE = 0.10, Z = -1.13, p = .259). None of the subsequent interactions showed an effect (ps > .123). Adding presence to the model did not increase the fit for predicting hit rate (Δ AIC = 1.3, $\chi^2(1)$ = 0.67, p = .413).

Moving beyond simple recognition, I next investigated the ability to discriminate previously seen objects from similar lures (following the approach outlined in Racsmány et al., 2021). Successfully identifying objects as 'similar' (i.e., lure discrimination) was not affected by whether the encoding and retrieval environments matched when encountering the old objects that generated each lure (β = 0.00, SE = 0.09, Z = 0.04, p = 0.965). This was also not affected by schema relevance (β = -0.08, *SE* = 0.10, *Z* = -0.83, *p* = .406) nor motor action (β = 0.10, *SE* = 0.09, *Z* = 1.07, *p* = .283). None of the subsequent interactions showed an effect (*p*s > .257). Adding presence to the model did not increase the fit for predicting hit rate (Δ AIC = 1.4, $\chi^2(1)$ = 0.61, *p* = .435).

Lastly, I investigated false-alarm rates for identifying similar objects as old. False alarm rates were not affected by the matching or mismatching encoding/recognition environments (β = 0.13, *SE* = 0.12, *Z* = 1.07, *p* = .285), schema relevance (β = -0.02, *SE* = 0.14, *Z* = -0.19, *p* = .847), nor motor action (β = -0.20, *SE* = .12, *Z* = -1.6, *p* = .108). Subsequent interactions also were not significant (*p*s > .196). Presence did not affect false alarm rate (Δ AIC = 1.4, $\chi^2(1)$ = 0.60, *p* = .440).

3.2.4 Specificity of Memory Recall

Our design allowed us to investigate the specificity of memory by combining both recall and recognition performance. Within the objects that were correctly recognized as ‘old’, free recalled objects were significantly more likely (β = 0.44, *SE* = 0.13, *Z* = 3.38, *p* < .001) to have lures that were correctly identified as ‘similar’ (*M* = 0.81, *SD* = 0.18), compared to objects that were recognized but not free recalled (*M* = 0.76, *SD* = 0.14).

3.2.5 Comparison with Subset from Study 1

To examine if the observed null results in key analyses might be driven by a reduction in power (due to a smaller sample size: here *N* = 60, compared to *N* = 240 in Study 1), I conducted complementary analyses within the Study 1 participants who experienced the same types of virtual environments (i.e., static kitchen and classroom environments). Within the subset of Study 1 participants, I observed a similar pattern of results for memory recall: marginally supporting evidence for the context-dependent memory effect (β = 0.17, *SE* = 0.09, *Z* = 1.83, *p* = .067), such that objects were more likely to be freely recalled in the same environment as encoding (*M* = 0.22, *SD* = 0.11) than in the other environment (*M* = 0.19, *SD* = 0.11). Additionally, schema relevance did not affect overall recall performance (β = 0.11, *SE* = 0.10, *Z* = 1.13, *p* = .260), and did not interact with the context-dependent memory effect (β = -0.00, *SE* = 0.18, *Z* = -0.01, *p* = .994).

Next, I examined hit rate within the subset of Study 1 participants. Because Study 1 did not manipulate when participants could or could not grasp each object, I restricted my models here to only replicate the context, schema, and interaction effects between these two – excluding a variable for motor action. I also did not observe the context-dependent memory effect (β = -0.13, *SE* = 0.10, *Z* = -1.13, *p* = .899), impact of schema relevance (β = -0.09, *SE* = 0.11, *Z* = -0.81, *p* = .420), nor an interaction between these two (β = -0.16, *SE* = 0.21, *Z* = -0.773, *p* = .440) relating to hit rate. Adding presence to this model did not increase the fit for predicting hit rate either (Δ AIC = 0.8, $\chi^2(1)$ = 1.27, *p* = .260).

The Study 1 subset of participants made marginally more false alarm judgments when the encoding/recognition environments matched (*M* = 0.12, *SD* = 0.08) than when they did not (*M* = 0.10, *SD* = 0.08; β = 0.27, *SE* = 0.14, *Z* = 1.95, *p* = .052). There was no effect of schema relevance (β = 0.01, *SE* = 0.15, *Z* = 0.08, *p* = .935) and no interaction with whether the encoding/recognition environments matched (β = 0.45, *SE* = 0.27, *Z* = 1.63, *p* = .100). Additionally, presence did not benefit the fit of the model (Δ AIC = 2, $\chi^2(1)$ = 0.03, *p* = .854).

While the sample size recruited for Study 2 was based on an a priori power analysis and related prior work, these comparisons with the subset of Study 1 participants suggest that I may have been under-powered to detect key differences in context-dependent memory that was evident in Study 1 (when I used a larger sample size).

3.3 Discussion

In this work I sought to understand the impact of motor action on memory recognition. I hypothesized that motor action (compared to merely viewing an object) would result in better memory retrieval and a stronger context-dependent memory effect. My study did not support these predictions as the opportunity to grasp an object did not benefit recognition memory. Furthermore, it did not differentially impact context-dependent memory effects, nor schema-relevance.

There are a number of possible explanations for why I did not observe the benefits to memory as expected. First, my design manipulated when participants could grasp (or not) objects during recognition, however, all objects had been grasped during the initial encoding phases. Had I manipulated which objects could be grasped during encoding, I might have seen those objects be remembered better. This difference in encoding/retrieval motor action is worthy of future research, as most prior work has investigated motor action during encoding. Hutmacher and Kuhbandner (2018) demonstrated the benefit of touch on recognition memory in two studies, but importantly this was in addition to grasping during encoding, not separate from it. This is only partially explanatory, as prior work has argued that there is little support for long-term memory benefitting from motor action during encoding (Zeelenberg & Pecher, 2016).

VR-based experiments, while an improvement over traditional laboratory-based experiments utilizing desktop computers and 2-dimensional stimuli, still have areas for growth. One limitation is the extent to which I was able to truly replicate participants' *grasping* of objects within a virtual space. Visually it appeared that participants' virtual hands were wrapped around a calculator and they moved in response to their own physical hand moving but participants did not receive any type of sensory or haptic feedback. Additionally, the physical hand motion required to grasp an object in VR is not always representative of a typical real-world physical grasping motion (e.g., the typical grasp for a mug and soccer ball differ, but would be the same in my paradigm. Thus, while I could approximate participants grasping and interacting with virtual objects visually, I could not replicate the full physical experience.

VR advancements and increased visual resolution has helped to get us closer to the macrogeometric properties of objects (Gallace & Spence, 2009), yet still the microgeometric properties remain elusive. Fortunately, this limitation may only exist for a limited time. Advances in VR gloves (as compared to the controllers used in this study) may be able to unlock more somatosensory features and feedback as technology continues to progress (Goupil et al., 2018).

With a smaller sample size than Study 1, I marginally replicated those findings of the context-dependent memory effect within free recall - a pattern of results that was similar to the subset of Study 1 participants experiencing the same contexts as Study 2.

Our finding that freely recalled objects were discriminable from other exemplars of the same object-type (in recognition) is evidence that memory draws on a richer representation than just the general gist of an object when recalling.

To summarize, object grasping and manipulation during recognition does not aid memory. Future work may study how object grasping and manipulation (vs not) during encoding may improve memory recall and recognition as well as better understand the role of touch and haptic feedback when grasping for objects.

4.0 Study 3: Exploratory remote VR Study

Study 1 and Study 2 were designed to study theoretically-motivated questions relating to context-dependent memory. I utilized VR paradigms as a tool for studying these questions due to its ecological validity and ability to get us closer to studying memory as it naturally occurs for people. Here, I wanted to push this idea even further by developing an approach to recruit participants not just from within our geographic location, but world-wide.

The motivation for such an approach was inspired by concerns about data collection when face-to-face participation is unavailable. Conducting remote research studies offers one opportunity to combat this issue, and recent advances have been made within this area, specifically with extended reality paradigms (Mathis et al., 2021). As further motivation inspiring us to delve into this type of data collection, Mathis and colleagues argue for the usefulness of research not only to inform about interactions in VR, but also for using the method as a proxy for real-world research (2021). My goal, therefore, was to recruit the same number of remote participants as I had recruited in the lab (N = 240, as part of Study 1).

Here, I present the outcomes of my attempt to conduct a remote VR study. Some problems I encountered were to be expected, however, others were surprising both in scale and time required to address. My hope is that this chapter can serve as a case study that future researchers may use as a guide for pitfalls to avoid, concerns to consider, and advice for anyone considering implementing a similar approach for their own research.

4.1 Methods

4.1.1 Participants

Thirty-two participants were recruited across the same four conditions used in Study 1 (relating to static and dynamic components). Participants were eligible if between 18 and 50 years old, currently reside in a majority English-speaking country, fluent in English, having normal or corrected-to-normal vision, not currently having a cognitive disability (such as a learning or attention disorder), being able to stand without interruptions for approximately 1 hour, and had access to an Oculus/Meta VR headset and Windows to use to complete the study. Participants were recruited through the Prolific platform (n = 29) and general online advertisements (n = 3). Participants resided in various countries around the world: United States (n = 20), United Kingdom/Great Britain/England (n = 10), Canada (n = 1), and Australia (n = 1). None of my participants' data needed to be excluded due to likelihood of low effort or attention in the encoding and distractor tasks (e.g., accuracy scores more than three standard deviations below the mean of the entire group). Four participants' audio recording files during the free recall task were not successfully uploaded during the VR paradigm, so they were excluded from any analyses involving free recall. My goal was to recruit the same number of participants as Study 1, N = 240. This target goal was based on the sample size for each condition I calculated as part of my a priori power analysis (power = 0.8) using parameters from Wälti et al. (Experiment 2; 2019) when matching contexts had a beneficial effect on free recall memory performance following the procedure outlined in Study 1. This sample size target for each condition was also in line with a recent VR study investigating context-dependent memory (Shin et al., 2020). Upon completion of the tasks, participants were compensated for their time with payment. See Table 4 for demographic information for all participants' data included in final analyses. The Institutional Review Board (IRB) approved all measures prior to data collection.

4.1.2 Procedure

All four conditions followed the same procedure, excepting the modifications to the environments described below. After meeting the eligibility screening criteria (via a Qualtrics survey), participants were assigned a participant number and instructed to download a compressed folder to their Windows machine. This folder contained the .exe file needed to run the VR paradigm, as well as all necessary experiment files and scripts used to upload data upon completion of the paradigm. After downloading, participants were instructed to start up the program and enter their participant number (the experiment files drew on this number and were saved in accordance with it, so that if a participant typed the wrong number, it was evident when data was uploaded) I did not use the VR tutorial as was used for the in-lab participants as the goal of it was to familiarize participants with moving around and interacting in VR. This was deemed unnecessary for participants who owned or had readily available access to their own VR headset. Upon starting the program, the participant was placed into a virtual hallway environment where they began the VR experiment by reading instructions for the encoding task. All subsequent tasks and processes of the VR procedure followed those of the in-lab participants.

Table 4 Demographic information

Condition (encoding - recognition)	N	Age	Gender	Number of Previous VR Studies
S-S	12	28.5 (8.0)	F: 2, M: 10, NB: 0	1st study: 2 1-5 studies: 10 6-10 studies: 0
M-S	4	33.5 (10.3)	F: 0, M: 4, NB: 0	1st study: 1 1-5 studies: 3 6-10 studies: 0
S-M	9	30.0 (8.3)	F: 0, M: 8, NB: 0	1st study: 2 1-5 studies: 6 6-10 studies: 1
M-M	7	28.0 (7.3)	F: 0, M: 7, NB: 0	1st study: 2 1-5 studies: 5 6-10 studies: 0

Note. Demographic information for analyzed participants. One of the virtual environments differed in background components being static (S) or containing motion (M) - within encoding or recognition (e.g., static during encoding, motion during recognition; S-M). Gender abbreviations: Female (F), Male (M), Non-binary (NB). *Non-binary* includes individuals identifying as non-binary or gender-fluid. Standard deviations in parentheses. One participant in the S-M condition did not report gender.

During each of the two encoding sessions, participants were introduced to a set of 30 individual objects (details below) that are typically found in one of the environments (e.g., spatula for kitchen; globe for classroom) or neither (e.g., bicycle). Participants were introduced to the objects without explicitly drawing attention to any type of relationship with the environment, nor told of any future memory tasks. Participants incidentally encoded the objects through a value-based sorting task. Each object individually appeared on a virtual countertop (kitchen) or desk (classroom) and was picked-up and moved by participants into one of two virtual boxes labeled "More than $20" or "Less than $20". After sorting the object, participants returned to the countertop or desk for the next object. After sorting all 30 objects in one environment, participants were relocated to a new virtual environment to sort a new set of 30 objects. This procedure ensured that participants interacted with the objects both physically (by picking them up and placing them) and semantically (by categorizing based on perceived cost). On average, participants spent 6.0 (Standard Deviation (*SD*) = 2.0) minutes completing both of these encoding sessions.

After the two encoding sessions, participants completed a five-minute distractor task of vocabulary and math questions, in the same hallway environment where they first started the experiment. Using either hand, participants selected the closest synonym (for vocabulary questions) or numerical answer (for math questions) from a set of three choices in text boxes. After five minutes of the distractor task, participants were relocated to one of the two earlier encoding environments (specific environment counterbalanced across participants) to perform a free recall test in which they were instructed to "describe out loud as many of the objects you had categorized into the boxes earlier as you can remember". On average, participants spent 1.4 (*SD* = 0.7) minutes attempting to recall objects.

Next, participants were relocated to the other (counterbalanced) encoding environment for testing recognition memory based on the Mnemonic Similarity Task (Stark et al., 2013). In this test, an object appeared in the same location as during encoding. These objects were either previously presented in one of the environments ("old"), a different exemplar of a previously presented object ("similar"), or a type of object not previously seen in the experiment ("new").

Participants used their hand or the object to touch a label indicating "old", "similar" or "new". Participants were instructed that they could grab and pick up the objects if that would help them make their decision. On average, participants spent 9.5 (*SD* = 1.7) minutes completing the recognition memory test.

Upon completion of the recognition memory test, all data (including free recall audio file) were automatically uploaded and stored using Google Cloud and Firebase. Participants were then instructed that they could remove their VR headset. Next, they returned to the Qualtrics survey to complete additional questions about demographics, VR experience, feelings of presence within each virtual environment (e.g., "Please rate your sense of being in the kitchen, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place"; adapted from Usoh et al., 2000), and the likelihood of finding each object in a typical kitchen or classroom.

4.1.3 Materials

During initial instructions, distractor task, and ending instructions, participants were placed into a virtual hallway with few background features. The encoding and retrieval tasks, two virtual environments were used: a classroom and a kitchen. The classroom environment consisted of background items such as desks, chairs, a bookshelf, windows with curtains, a blackboard, a clock, etc. The kitchen environment consisted of kitchen cabinets, chairs, windows and curtains, sink, kitchen appliances, tea kettle and pot of water on the stove, stand mixer, and a clock. For the static-only condition, all background objects were unchanging. For motion conditions, the kitchen background objects were made dynamic: curtains blowing in the wind, spinning electric-mixer, steaming tea kettle, boiling pot of water on the stove, rotating clock hands, and running sink faucet.

I used the same objects as in Study 1, based on the previous norming study (See Appendix A), including 40 kitchen objects expected to be found in a kitchen, 40 classroom objects expected to be found in a classroom, and an additional 40 miscellaneous objects that are not expected in either environment. Ratings from participants in a post-VR survey confirmed my selection of objects (see Table 5). An additional 120 exemplars of the same type of object served as lures during the recognition memory test. Each lure's orientation matched its associated target object. Each participant saw a random subset of objects (10 from each object schema in each environment for a total of 60 encoded objects), counterbalanced as target or lure.

Table 5 Object Schema Ratings

Object schema	Kitchen rating	Classroom rating
Kitchen	6.6 (0.3)	1.2 (0.3)
Classroom	1.7 (0.6)	6.2 (0.6)
Miscellaneous	1.4 (0.4)	1.8 (0.6)

Note. Object schema ratings from analyzed participants on a 7-point scale of where an object would typically be found (1 = not very likely, 7 = very likely). Standard deviations shown in parentheses.

4.1.4 Free Recall Scoring

Audio recordings of the free recall were first transcribed using Microsoft's *Transcribe* feature and confirmed by a human researcher. Then, two independent coders separately identified the objects described in the recordings (94% consistency) with discrepancies settled by a third independent coder.

4.1.5 Hardware

All VR tasks were completed by participants in their own space (not in the laboratory). I restricted participation to only those with access to an Oculus/Meta headset (as the VR paradigm was specifically designed and tested using such headsets and I wanted to avoid technical issues which may arise from incompatibility with other headsets) and connection to Windows. Participants reported using various Oculus/Meta headsets available: Oculus Rift, Oculus Rift S, Oculus/Meta Quest, Oculus/Meta Quest 2 (some used a link cable while others used a wireless connection to link to their PC). VR tasks were coded with the UXF framework (Brookes et al., 2020) within Unity (version 2018.3.14). Virtual environments and objects were downloaded from the Unity Asset store (https://assetstore.unity.com/) or Sketchfab (https://sketchfab.com/) and modified within Unity to cohesively match (e.g., realistic size) within the environments.

4.1.6 Statistical Analyses

To analyze memory performance data, I conducted separate logistic mixed-effects regression models (Baayen et al., 2008). For memory recall, I predicted whether a participant recalled an object they had seen before. For memory recognition, I conducted three separate models to individually investigate hits, lure discrimination, and false alarms (following the approach used by Racsmány et al., 2021), unless otherwise noted. I controlled for the presence of background motion by using separate fixed effects terms for encoding and retrieval. When investigating participants' ratings of presence, I used the average rating from the six questions of the presence questionnaire, for each environment. Each regression model included random effects for participant and object. For ease of interpretation, figures depict averages at the participant level.

4.2 Results

4.2.1 Memory Recall

I examined the context-dependent memory effect for objects learned within two separate virtual environments. I also investigated how schema affects context-dependent memory. All participants recalled at least one object from each of the two environments.

I did not observe evidence supporting the context-dependent memory effect ($\beta = 0.10$, *SE* = 0.14, *Z* = 0.708, *p* = .479).

Examining overall recall (without considering whether encoding and retrieval contexts match), objects that were schema-relevant with the encoding environment (e.g., learned spatula in kitchen) were more likely to be freely recalled than schema-irrelevant objects (e.g., pencil sharpener in kitchen; $\beta = 0.42$, *SE* = 0.15, *Z* = 2.89, *p* = .004). Schema relevance with the encoding environment interacted with the context-dependent memory effect ($\beta = 0.68$, *SE* = 0.28, *Z* = 2.40, *p* = .016), such that the context-dependent memory effect was marginally statistically significant for schema-relevant objects ($\beta = 0.43$, *SE* = 0.23, *Z* = 1.91, *p* = .056), and not schema-irrelevant objects ($\beta = -0.24$, *SE* = 0.18, *Z* = -1.33, *p* = .183), see Figure 4. I next added to the model a fixed effect term representing participants' ratings of presence in the corresponding encoding environment. This did not result in a better model fit (Δ AIC = 0.7, $\chi^2(1) = 1.28$, *p* = .257). Because there were so few participants in each condition, I did not analyze potential differences due to motion within the encoding environments.

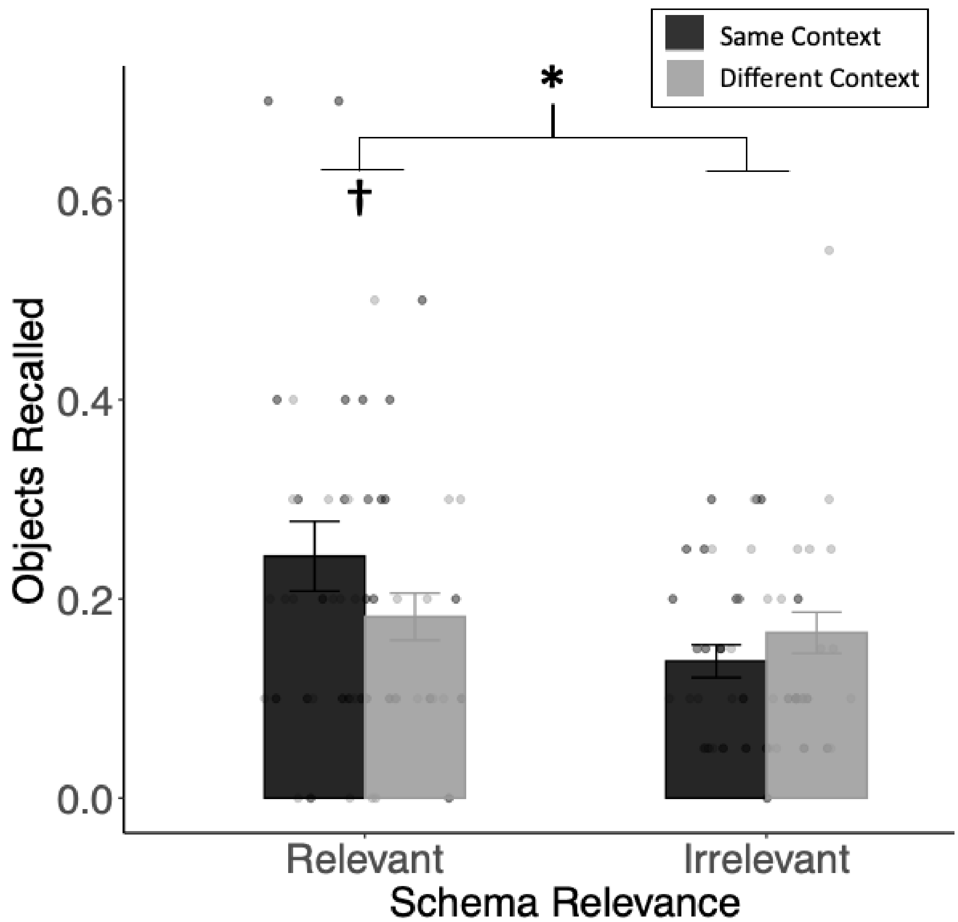

Figure 4 Average ratio of objects recalled when encoding and retrieval environments are the same or different, and objects were relevant (or irrelevant) with their encoding environment. Error bars represent SEM. * represents *p* < .05; † represents *p* < .1

4.2.2 Memory Recognition

Having examined memory recall, I next investigated memory recognition. My design allowed us to investigate the specificity of participants' memory by testing participants' ability to recognize objects that were old, similar (to previously seen items) or new.

First, I investigated differences in hit rate (correctly identifying an object as seen before). None of the investigated variables indicated effects predicting hit rate (all *p*s > .233), nor did adding presence help the fit of the model (Δ AIC = 1.5, $\chi^2(1) = 0.52$, $p = .472$).

Moving beyond simple recognition, I next investigated the ability to discriminate similar lures from previously seen objects. None of the investigated variables indicated effects predicting mnemonic discrimination (all *p*s > .269). In contrast to the model with hit rate, adding presence improved the fit of the model for predicting mnemonic discrimination (Δ AIC = -2.2, $\chi^2(1) = 4.24$, $p = .039$), such that every one point decrease in feeling of presence increased the odds of successful mnemonic discrimination by 1.23 times.

Lastly, I investigated false-alarm rate for identifying similar objects as old. False alarm rates were not related to any of my investigated variables (all *p*s > .244). Adding presence resulted in a marginally statistically significantly better for of the model (Δ AIC = -1.4, $\chi^2(1) = 3.32$, $p = .069$), suggesting that every one point increase in feeling of presence increased the odds of making a false alarm by 1.21 times.

4.2.3 Specificity of Memory Recall

Our design allowed us to investigate the specificity of the recalled objects in memory by asking how well free recalled objects were discriminated from their lures (while keeping successful recognition constant) . Of the full set of objects that each participant correctly recognized as ‘old’, those that had been free recalled were significantly better discriminated ($\beta = 0.46$, $SE = 0.20$, $Z = 2.26$, $p = .024$) from their similar lures (‘similar’ hit rate: $M = 0.82$, $SD = 0.17$) than were non-free-recalled recognized objects (‘similar’ hit rate: $M = 0.75$, $SD = 0.12$).

4.3 Discussion

Here I replicated a number of key findings from Study 1 within a separate sample of participants, recruited from multiple majority English-speaking countries around the world. Though I was unable to conduct planned comparisons between the data collected remotely and those collected in the lab, it is comforting to see similarities in the findings for two studies utilizing separate and unique methods of data collection.

I observed a benefit to memory recall when the encoding/recall contexts matched *and* the object/context relationship was schema-relevant. This finding suggests that the objects which are schema-relevant during encoding are more easily incorporated into the context, thus allowing the contextual cues (when appearing later during recall) to aid in memory performance. Additionally, I also replicated the finding suggesting that people not only remember the gist of a given object, but that they store and are able to retrieve detailed information about the object.

Furthermore, I observed an interesting pattern in which presence was related to both mnemonic discrimination and false alarms. It appears that both may work in conjunction with each other, as the decrease in presence benefitted mnemonic discrimination, and increasing it resulted in more false alarms. Increases in immersion and feelings of presence have resulted in mixed outcomes relating to memory performance (Smith & Mulligan, 2021). This pattern of results requires further investigation as it was not replicated in Study 1 nor Study 2, and a more controlled set of experiments would be required before concluding that increased feelings of immersion and presence act as a detriment to one's memory.

The remaining focus of this chapter pertains to the pros, cons, and additional considerations I have learned as part of this methodological endeavor to deploy a remote VR study.

4.3.1 Pros

By implementing a remote data collection approach, I was able to recruit a more geographically-diverse sample of participants that could be recruited to be brought into the laboratory space. Though I restricted my participants to only those residing in majority English-speaking countries, I still obtained data from participants in three continents: North America, Europe, and Australia. In addition to the increased geographic diversity, I also saw a more diverse participant sample with respect to age, education level, and prior VR use and experience compared to the in-lab participant sample.

Even without the ability to provide direct feedback in case questions arose during the VR paradigm or meet face-to-face to troubleshoot any hardware of software issues, data collected were comparable to the data collected in the laboratory. By not needing to be *on-hand* to collect each participants' data, participants could complete the study at their earliest convenience, regardless of time zones or researcher availability.

As expected, participants' prior VR experience and exposure was greater than the in-lab participants. All participants in Study 3 indicated *gaming* as a reason for their own VR use except one participant who indicated *VR travel*, in addition to *Development or Research*. Additionally, all participants reported being *consumers of VR products and* applications. This increase in prior VR experience and exposure allowed us to not have to teach participants how to use the controls or interact with objects in a virtual space. Additionally, it reduced concerns that the VR experience itself may impact participants' performance on the memory tasks.

4.3.2 Cons

Though suggested as a potential advantage of remote data collection for VR studies (Ratcliffe et al., 2021), the rate of participation was the major detriment to the usefulness and planned analyses for Study 3. Over the course of five months, I was only able to collect usable data from 32 participants. I first used Prolific (https://www.prolific.co/) to recruit participants because it is a platform dedicated to online research studies. When data collection was slower than anticipated, I turned to a more general advertising approach in an effort to collect data from participants who were not signed up via the Prolific platform. I posted advertisements to participate in my study on various Reddit threads, Facebook groups, Discord servers, and even a website dedicated to remote extended reality studies (https://www.xrdrn.org) with little success in improving the rate of data collection.

In addition to the requirement of participants to have a Prolific account in order to first access my study, the cost of recruiting through such a platform due to the fees associated with it should be a major consideration. In addition to paying participants, the platform charged a percentage fee for each paid participant. These fees and costs can quickly add up, even with relatively slow rates of data collection, and especially if participants' data ends up needing to be excluded from analyses.

While this was not a frequent issue in Study 3, there were some instances when a participants' data were not uploaded correctly to the online data storage system. It was difficult to identify the cause of this issue and aside from messaging participants and requesting them to submit files individually, there was little that could be done when these problems were encountered. Some participants were able to provide the requested data files after messaging, though this would not be a reliable process for larger-scale data collection needs.

While the remote data collection had its advantages in recruiting a more diverse sample of participants based on a number of factors, accessibility to VR technology and headsets is still a limitation. By restricting participation to only those who owned or had easy access to a headset I may be limited in the types of generalizations I can make resulting from this small portion of the population. As technology improves, hopefully VR headsets become more affordable so that more people can participate in future remote VR studies.

4.3.3 Recommendations for Future Research

In this section, I aim to provide suggestions and recommendations for anyone who may be considering a similar approach to remote data collection for a future VR study.

First, I would encourage researchers to attempt to create studies that are compatible with multiple VR headsets and/or across multiple platforms. While this may not be feasible for all studies, it may greatly broaden the available participant pool. In addition, recent developments have made running programs developed by others more accessible to a wider audience. This not only could help increase the rate of data collection, but it could also prevent participants from needing to download files in order to be able to participate in a study. This streaming alternative could speed up the process not only of accessing a study, but also of uploading any relevant output files resulting from participation in a study.

With this in mind, if possible, I believe that reducing the need for participants to download files in order to run the VR study would help increase the rate of data collection. I observed feedback and criticism that running a .exe file which had been downloaded from a stranger's post on the internet was an excellent way to get a virus or other malware into one's computer. While valid and a fair criticism, I would encourage future researchers to potentially avoid such issues of trust by increasing their researcher/potential-participant interactions. This could be achieved through more direct contact to share any files (if needed to be downloaded), or through an initial meeting over software such as Zoom so that participants feel more comfortable with the researcher and the research project. Of course these approaches have their own drawbacks including increased time required of the researcher. But this may be worthwhile to alleviate concerns or apprehensions that potential participants may have prior to agreeing to participate in a study.

While this study did not progress as expected due to the issues described here, it still represents a potentially advantageous opportunity for future researchers. Additionally, as technological advances continue, some of the issues encountered here may become obsolete, or at least less problematic for future research endeavors.

5.0 General Discussion

Across three studies, I investigated the context-dependent memory effect and which factors may result in its occurrence (or absence). The findings highlighted the role that schema-relevance of an object/context relationship has in conjunction with matching encoding/retrieval contexts on subsequent memory. Through the design, I concluded that the schema-relevant objects were more easily integrated into the context, thus benefiting memory even without external direction or guidance towards the object/context relationship. Additionally, I identified an advantage of context-dependent memory when recognizing previously seen objects, and also observed a disadvantage in increased false alarms when encoding/recognition contexts matched.

In addition to serving as a partial replication of a few key findings from Study 1, Study 2 did not find evidence that picking up and moving an object would benefit recognition memory compared to when a person just looked at the object. Lastly, Study 3 explored attempts to make my VR paradigm even more accessible and ecologically valid by implementing an approach to complex remote data collection.

Taken together, these studies represent a feasible approach to studying context-dependent memory effects within a naturalistic design. Furthermore, they advance our knowledge about factors which lead to (and do not lead to) benefits of memory when contexts are the same or different from initial learning.

Table 6 Factors Helping or Hindering Memory

Factor	Study 1	Study 2	Study 3
Same E-R context	Helps recall, Helps recognition (*marginal effect*), Hinders recognition	Helps recall (*marginal effect*)	No effect
Schema-Relevance	No effect	No effect	Helps recall
Same E-R context & Schema-Relevance	Helps recall	No effect	Helps recall
Increased feelings of presence in encoding context	Helps recall	No effect	No effect
Dynamic contexts	Hinders recognition	-	-

Note. Same E-R context refers to matching encoding/retrieval contexts. *Schema*-Relevance refers to the relationship between the object and the encoding context. *Helps recall* measured using free recall memory task. *Helps recognition* measured with hit rate. *Hinders recognition* measured with false alarm rate. *No effect* indicates no statistically significant differences observed.

5.1 Context-Dependent Memory Effects

While context-dependent memory effects have not always been reliably reproduced both inside and outside of the laboratory (Smith & Vela, 2001), here I present evidence supporting the beneficial role that matching encoding/retrieval contexts can have on both recall and recognition memory. Study 1 showed this effect most clearly by finding that objects were both recalled better *and* were more correctly recognized as having been seen before when they were tested in the same context as where they had been first learned. Although this memory benefit is encouraging and suggests a useful strategy for improved memory performance, it is not without a drawback. This detriment takes the form of increased false memory judgments (i.e., incorrectly judging an object as having been seen before when it is only similar to another object which had actually been seen). These findings are in line with prior research which also showed a beneficial context-dependent memory effect in hit rate, but a detriment in false alarms (Racsmány, 2021; Alakbarova et al., 2021). It is likely that the contextual cues arising from the matching encoding/retrieval contexts that help memory, could also be the cause of the incorrect false alarms. Because the similar objects likely share many features with the target (i.e., the object which had been seen) such as orientation, schema-relevance with the context, size, shape, etc., it follows that participants may have experienced worse memory performance due to feelings of familiarity induced by the many overlapping features.

The studies presented here primarily focused on semantic and visual factors that could have resulted in context-dependent memory effects. There are, however, other factors relevant for the idea of a context. For example, stimuli that draw on different or multiple senses may increase the likelihood of observing these effects. In fact, changing olfactory cues have resulted in context-dependent memory effects even when visual cues did not (Pointer & Bond, 1998). It is also important to note that when I manipulated the richness of the visual cues present in the context (e.g., when the background objects changed from static to dynamic), I did not observe differences in memory as I had expected. Future research may investigate whether changing visual cues in conjunction with modifications to olfactory cues (such as food-related odors) or auditory cues (such as students conversing in a classroom) may result in stronger context-dependent memory effects. Advancing technology makes these considerations more feasible and such additions could bring the experience even closer to the real-world (Reggente, 2023).

5.2 The role of Schema

In addition to observing the context-dependent memory effect within Study 1, I also found that that this effect interacted with the schema-relevance of the relationship between the object and where it had been encoded to result in better memory recall. This finding is exciting because it suggests that the contexts were not only incidentally encoded along with the objects, but that the relationship between the object and the context played a key role in this successful integration. Objects that were not relevant for the schema in which they were encoded did not experience the same benefit to memory when the encoding/recall contexts matched, as those objects which were schema-relevant. This finding suggests that not only is the object-context relationship important for context-dependent memory effects (Shin et al., 2020), but that it does not require external direction towards it.

This finding is informative for our understanding of theories explaining when context-dependent memory effects are likely to occur (or not). Whereas the overshadowing theory would predict that schema-related objects should mask any impact of encoding context (Smith & Vela, 2001), I found the opposite to be true. Instead, it appears that the schema-relevance between the object and the encoding context helps to integrate the object into memory. It is likely that the existing schema one has for a kitchen (or a classroom) gets updated when additional schema-relevant objects are encountered during encoding and therefore incorporated into the context (Polyn & Kahana, 2008; Pacheco et al., 2017). This facilitation of objects into the context can then improve subsequent recall due to the increased contextual cues available.

This explanation may also help us understand when context-dependent memory effects are observed. Like me, Shin et al. (2020) observed context-dependent memory effects within items deemed to be relevant to the encoding context. Improvements in memory performance can be expected when two conditions are met: 1) matching encoding/retrieval contexts and 2) a relevant relationship exists between the to-be-remembered items and the context. This relationship may be attention-directed as is the case when people are explicitly instructed to consider directly linking the item with the context. Importantly, this explicit instruction is not always necessary, as evidenced in this set of studies, where people may have incidentally relied on prior semantic knowledge and familiarity of the relationship. In both explicit and incidental cases, however, this relationship is beneficial to memory when the encoding context is reinstated during retrieval. When this item-context relationship is not formed, or when to-be-remembered items do not fit with the schema of the encoding context, memory does not improve even when encoding contexts are reinstated. Failure to meet these conditions could explain why context-dependent memory effects were not reliably observed in Wälti et al. (2019). Their stimuli (words to be remembered) were carefully selected to exclude any apparent item/context relationships. Without this relationship, it may have proved too difficult for participants to successfully link the item with the context (especially without explicit instruction to do so – only to attempt to memorize them), therefore explaining why they did not observe context-dependent memory effects.

In furtherance of the key role of the item/context relationship, my findings are in accordance with results suggesting that context-dependent memory effects can be observed when the reinstated context is semantically similar to the encoding context, rather than visually exactly the same (Smith et al., 2014). In a series of experiments conducted by Smith and colleagues, the context provided at retrieval was varied as to be either: the same as that during encoding, conceptually similar and visually similar though not the exact same episode, or conceptually similar though not visually similar. This was achieved using naturalistic videos as stimuli so as to capture the semantic aspect of a context (e.g., people playing soccer), while also being able to experimentally vary the visual aspects (i.e., by showing a different video of other people playing soccer). In all instances, the context-dependent memory effect was most strongly observed when the encoding/retrieval contexts were the exact same. Benefits to memory retrieval, however, were also observed in the instances when the retrieval contexts were merely semantically similar to the encoding contexts. These outcomes provide further evidence of the value that the schema or semantic aspect of the context itself provides, but it also helps speak to other principles regarding context reinstatement (Smith et al., 2014). Notably, this suggests that the encoding/retrieval context match should be considered as a type of gradient, where the more closely aligned the two are, the better for memory outcomes. Future research may extend the commonalities between these experiments and my own by manipulating the similarity between the contexts used. For example, one might consider that a classroom and a kitchen, as used in my studies, are vastly different. However, one could also argue that they are similar because they are rooms found within a house.

Using an open, outdoor soccer field as an alternative context may result in more pronounced context-dependent memory effects.

Additionally, my studies also help address a potential concern that the VR headset itself may have served as a form of context. Because we observed a context-dependent memory effect when either the classroom or kitchen contexts matched, we can feel confident that this effect was not driven by participants wearing the headset and using the controllers. These VR-components were present and remained the same while participants completed all of the VR-tasks.

In Study 1, I provide evidence that this finding is not just driven by participants naming objects typically found in that context, as schema-relevance alone did not predict memory recall ability. Put another way, objects that were learned in a context where they would typically be found were not better remembered than those which were learned in a different context.

I replicated this interaction effect between schema-relevance and context-dependent memory effects in Study 3, though saw a slightly different pattern of results for the individual context-dependent memory effect and role of schema-relevance. Objects were not better recalled when encoding/recall contexts matched, but schema-relevant objects were better recalled than schema-irrelevant objects (regardless of matching or mismatching encoding/recall contexts).

5.3 The impact of the context itself: the role of motion and presence

I had expected that the presence of motion would benefit memory and increase context-dependent memory effects. This was not the case as the impact of dynamic background components present in the contexts was sparse and inconsistent. I anticipated that the dynamic contexts would have an advantage over the static contexts because of the increased salience of the context's feature information. If the dynamic components resulted in stronger contextual awareness (i.e., a more prominent schema of a *kitchen*), we would have expected to observe stronger context-dependent memory effects. In comparison to previous studies which found context-dependent memory benefits when using video backgrounds (Smith & Manzano, 2010), it is likely that my dynamic components were not salient enough to serve as a meaningful memory cue. The inability to observe context-dependent memory effects relating to motion could also be due to the level at which the motion is present within the context. Recent research has shown that dynamism impacts memory for details concerning a scene, but not of specific objects (Romero et al., 2023). It is likely then that I did not observe a memory benefit within my participants because they had been tested on their memory for individual objects presented within dynamic (or static) contexts.

Though not my expectation, this diminished role of motion could be thought of as support for the role of semantic representations comprising a context. If changing from a kitchen with dynamic background components to the same kitchen containing only static background components had resulted in context-dependent memory effects, it would suggest that the presence of motion should be considered as a key component of a context. Instead, it appears that the gist of the context, or its representation as a *kitchen* or a *classroom* is more important.

This fits nicely with findings observing that the semantic components of a context are relevant for context-dependent memory effects (Smith et al., 2014; Bramão et al., 2017).

In a similar vein as the ideas of schema-relevance between the object and the context, future research may consider testing the impact of motion when it is expected (or required) within a context. Though I tried to mimic this with realistic or expected dynamic kitchen components, they may not be vital enough to our representations of what a *kitchen* is to have had much of an impact.

Instead, future studies may implement background motion while participants are placed in a virtual car driving along a highway. In this context, one would more likely expect to see changing components and more dynamic aspects than when placed in a kitchen.

I anticipated that, had I found effects relating to motion, one potential mechanism could be that they increased feelings of immersion and presence within a given context. Because I did not observe robust effects of motion, it does not appear that this is likely. Feelings of immersion did appear to play a role in recall, when participants recalled more objects when they had encoded them in a context in which they felt a greater sense of presence. Perhaps the environments used in my studies were not distinct enough to evoke the type of differences in feelings of presence that would result in increases in context-dependent memory.

5.4 Object Grasping did not benefit Recognition Memory

In Study 2, I focused on the role that grasping an object may have on improving memory recognition. In a sense, had I found support for improved memory recognition, I could have argued that the action of reaching toward and grasping should be considered as a part of the context. Since all participants encoded the objects during a task which required picking up and moving the objects, any differences in memory performance (between grasping and simply pointing) could have reflected the role of grasping. Additionally, it could then have also been considered a potential factor of context-dependent memory (due to the same encoding/recognition action). Because I required participants to grasp all objects during encoding, I am unable to draw any conclusions about the role grasping may play during encoding and its effect on subsequent memory.

5.5 Memory Formats: Free Recall & Recognition

Rarely are context-dependent memory effects studied using both recall and recognition tests. Because of my relatively novel approach, I was able to investigate how recalled objects were differentially recognized and in what ways such differences might inform us about memory. I found evidence supporting the notion that people are not just remembering the gist of an object (e.g., *I remember seeing a basketball*). Instead, they are remembering individual components of that object which allow them to correctly discriminate between multiple exemplars of the same object type (e.g., *I saw the completely orange basketball, not the orange and white basketball*). This effect was present in all three of my studies, suggesting a robust and reliable effect of the content stored in memory, as opposed to simply a label for that memory.

This finding can be contemplated in light of the fuzzy trace theory (Reyna et al., 2016) and its suggestion that memories are stored as two separate entities: verbatim and gist representations. Though memories may be stored in both formats, my results indicate that they can both be affected by the same factors, such as matching encoding/retrieval contexts. My findings in Study 1 support this notion. Matching contexts benefitted free recall performance, which presumably only needs to draw on gist representations to be successful. For example, participants could have merely recalled seeing a "basketball" without specifying that it was the color orange or that it included a "WNBA logo" on the side of it, which would draw on the verbatim representations. These matching contexts, however, hindered recognition memory accuracy through increased false alarms. In this case, ineffective verbatim representations can result in false alarms even if gist representations are functioning properly. For example, one might recognize that they had seen a spatula before, but if they do not draw on the correct verbatim representation that they had seen a red spatula and not a green spatula, then this can result in a false alarm.

While the conclusions described above suggest that the verbatim and gist representations may be separate, they may not be entirely independent of each other. Support for this notion comes from my relatively novel analysis involving both free recall and recognition. Though I cannot rule out the possibility that participants were drawing on verbatim representations during free recall, if these two were entirely independent, then we would not expect to find differences in recognition performance based on a measure of free recall performance.

In my studies, I controlled for potential confounds during the recognition test by presenting both exemplars (target and foil) in the same orientation when it appeared in the environment. This way, participants could not rely on orientation alone as a cue/indicator for making their recognition response. Though I can rule out orientation as a helpful feature for recognition memory, future work might probe further which differences between to-be-remembered items are most determinative of successful recognition and mnemonic discrimination.

5.6 Implementation of Virtual Reality Methodology

The studies presented here involved a number of potentially impactful methodological approaches. I build upon prior research demonstrating the utility and benefit of VR as not only a tool for studying memory (Smith, 2019; Iriye & St. Jacques, 2021), but also specifically context-dependent memory (Essoe et al., 2022; Shin et al., 2021). This methodological approach allowed us to easily move participants from one virtual environment to another. I also was able to present three-dimensional objects to be learned, as opposed to photographs or words representing the object. While this is advantageous from the perspective of wanting to more closely mirror *real-world* learning, it increases complexity with respect to task demands, in particular relating to free recall. Because I introduced participants to objects they could see and grasp, the free recall process required an additional step not present in prior VR studies investigating context-dependent memory (Shin et al., 2021). For example, my participants needed to map the visually-presented object onto a semantic label or object name in order to successfully recall it. Any confusion or misunderstanding of what an object *was* during encoding would then detrimentally affect a participants' ability to verbally recall that object, compared to simply recognizing the visually-presented object.

While the studies presented here did succeed in identifying context-dependent memory effects within more realistic environments, it still leaves open the question as to whether VR is the best medium through which to study these effects. Though VR methods have been suggested to more closely resemble real-life memory retrieval (compared to traditional, laboratory-based approaches (Kisker et al., 2019), we may still consider VR as a stepping stone within a larger journey towards studying real-world learning and memory. We tried to mimic the real-world as much as possible, still there are certain drawbacks and limitations that VR methods cannot overcome. For example, in each of my studies participants wore headsets and used controllers to interact with the objects and contexts. Though we hoped participants would feel immersed in the environments they were placed into, it is still possible that they may have represented the feeling of being in VR as a component of the context, particularly those participants who had never used such technology before.

Recent work provides optimism that we, as a field, are making progress on better being able to study how memories are formed and subsequently retrieved in real-world and applied scenarios. For example, researchers have found success in improving our understanding of how well people remember minor background details using video and eye movement recordings (Misra et al., 2018). Misra and colleague's demonstrated methodological advances helped to shed light on notions concerning just how much surrounding stimuli is encoded into memory during real-life activities and able to be subsequently recognized later.

With such methodological advancements in mind, recent work has revisited studying context-dependent memories in the real-world, as was done nearly 50 years ago (Godden & Baddeley, 1975). Using updated technology, context-dependent memory effects have been observed for spatial location information, tracked using smartphones and GPS tracking (Choi et al., 2023). Similar to the findings of Godden & Baddeley (1975), the context-dependent memory effect was observed, using more technologically advanced and ecologically valid measures.

5.7 Limitations

Though the studies presented here have strengths and applicability for future researchers, I wish to comment on two limitations which could be considered when drawing conclusions. The first relates to the time between encoding and memory testing. I implemented a five-minute distractor task as an attempt to eliminate any recency memory effects during the free recall task. This time-frame may have impaired our ability to detect context-dependent memory effects, as with a shorter duration, the need to draw on contextual cues may be less important than it would be with a longer duration between encoding and retrieval (Smith & Vela, 2001). Though this is a concern and I did not manipulate differences in time between these important phases, a recent VR study (Shin et al., 2021) which found evidence of the context-dependent memory effect, did not observe an interaction between the effect and a study-test delay (immediate retrieval vs next-day retrieval).

A counter-argument to this concern is that my approach allowed participants to stay immersed in the VR headset for the entirety of the VR paradigm. Moving out of VR and back into the *real-world* before entering VR again can have adverse effects on participants and their memory (Lamers & Lanen, 2021). Additionally, I believe my approach helped limit the frequency of motion-sickness within my participants, particularly when considering how many of my participants had never used VR before.

The second limitation mainly concerns Study 2 and 3, as due to their smaller sample sizes, it is likely that they were under-powered to be able to observe the same effects as I saw in Study 1. Though Study 3's findings were more similar to Study 1's findings, this could be due to differences in the sample of participants. Study 3's participants all had easily accessible VR headsets and prior experience using VR. This experience most likely reduced the novelty of the *VR experience* and allowed participants to focus solely on the tasks. In Study 1 and 2, effect sizes may have been diminished due to potential reductions in focus or attention to the task, as the initial exposure to VR may have distracted some participants. I attempted to combat this concern by implementing a tutorial to expose participants to VR prior to beginning the study, but this is hardly an adequate substitute for experience afforded by consistent use of a VR headset. It is possible then, that the smaller sample size for Study 2 may not have been able to overcome these effects in the same way that Study 1 could (since it had a larger sample size).

5.8 Conclusions

I sought out to determine when and how context-dependent memory effects arise. Through three immersive virtual reality studies, this work builds on the foundational studies positing the benefits of context-dependent memory. Matching encoding/retrieval contexts were beneficial for memory recall and recognition, though also resulted in more false alarm judgments. Furthermore, the schema-relevance of an object within the context where it had been encoded increases the benefits of the context-dependent memory effect. This effect appeared even without directing attention to the object/context relationship. The inclusion of dynamic background components did not consistently benefit memory, nor did increased feelings of immersion. Additionally, interacting with an object did not improve recognition memory compared to merely looking at the object. I did, however, gain insight into the nature of the content of an object stored in memory. I provided evidence that people represent (and can retrieve) specific details about remembered objects, not just the semantic gist of the object. The findings presented here increase our understanding of the factors at play within our memory systems and can be useful for identifying when we will be most likely to remember.

Appendix A Norming Study

In order to examine one of the key components of my VR studies, schema relevance between the object and the context, I first needed to identify objects which would be expected to be found within each of the environments (kitchen and classroom). In addition to being found in one of these contexts, ideal objects would also likely not be found in the other. Lastly, I needed miscellaneous objects that would not likely be found in either of the environments.

To identify potential virtual objects, I first identified 100 common objects thought to meet each of these criteria (See Appendix A.1, A.2, and A.3). Using predominantly Sketchfab (https://sketchfab.com/) and other websites housing publicly accessible virtual objects, I created two-dimensional images of each of the potential virtual objects, then placed them on a blank background. Of these 100 objects for each categorization, my goal was to identify 40 objects that would be most ideal to be used as part of the VR studies based on how they were rated for being found in each of the environments.

I analyzed data from 44 participants (19 female and 25 male; M_{age}: 19.2 years, SD_{Age}: 1.2 years) who provided ratings on the potential objects and were subsequently compensated for their time with course credit. All participants self-identified as being older than 18 years old, having normal or corrected-to-normal vision, not currently having a learning or attention disorder, and did not experience any adverse technological issues impairing their ability to complete the study.

I did not analyze ratings from any participant who did not identify as a native English speaker. Additionally, I did not analyze data from any participants who failed either of my two sense checks. In the first, I asked participants to "identify what this place is" and indicate their familiarity with it using a 7-point Likert scale (where 7 indicated very familiar and 1 indicated not very familiar) and two-dimensional images of potential virtual environments (separately for a kitchen and classroom). Additionally, randomly interspersed among the objects, I used three attention check trials (requiring participants to type in a specified value). Ratings from any participant who indicated a familiarity of less than 4 for either environment or who answered 2 (or more) of the attention check questions incorrectly were not analyzed.

I used Qualtrics to create an online study to easily collect participants' ratings about the objects. After consenting to participate, receiving brief instructions, and completing the environment familiarity-rating questions, participants were shown a two-dimensional image of a virtual object. They were first asked to "identify what this object is" by typing the name/label for it and then were asked to indicate how familiar they were with it (using the same 7-point Likert scale described above). Next, they were asked to provide ratings about how likely it would be found in a kitchen (using a 7-point Likert scale where 7 indicates very likely and 1 indicates not very likely). I used the same two-dimensional image of the kitchen they had responded to earlier, rather than supplying the term "kitchen" to them when asking for their ratings. I then followed this same approach to ask about the object's rating within a classroom. In total, each participant provided ratings for 150 objects (50 potential kitchen, 50 potential classroom, and 50 potential miscellaneous/neither) presented in a random order. Subsets of objects were randomly presented to different participants.

Information about the number of participants providing ratings, as well as average ratings for objects in each environment are summarized in Table 7 below.

I used the ratings for each object to determine a final set of 40 virtual objects (See Appendix B) expected to be found in a kitchen, classroom, and neither of these two (labeled as *miscellaneous*). For the kitchen and classroom objects, I selected objects that had the greatest difference in terms of ratings between the two environments (e.g., an object receiving a high *kitchen* rating and low *classroom* rating). For the miscellaneous objects, I selected objects that had the lowest combined rating for *kitchen* and *classroom* as that indicated that they were not likely to be found in either environment. Figures in Appendix A.1, A.2, and A.3 reflect this ordering approach (most ideal objects on the left side and least ideal objects on the right side). Final objects were decided upon based primarily on the ratings metric described above, however, some objects were not used due to: inability to be downloaded, inability to be integrated into my VR paradigm, similar object already present in the background of one of the environments, or if a second similar object (to be used as foils in the VR studies) was not available. Because of these issues, some objects used in the VR studies were not the exact same as those shown during the Norming Study, so ratings were also collected as part of the VR studies to confirm object-environment categorization.

Table 7 Ratings for objects in norming study

Expected Environment	Mean # Raters *(SD)*	Min. # Raters	Max. # Raters	Mean Rating in Kitchen *(SD)*	Mean Rating in Classroom *(SD)*	Mean Familiarity Rating *(SD)*
Kitchen	22 (2.6)	16	28	6.4 (0.7)	1.9 (1.1)	6.3 (0.8)
Classroom	22 (2.7)	17	30	2.6 (1.3)	5.7 (1.2)	6.1 (1.0)
Miscellaneous	22 (2.7)	15	29	2.2 (1.1)	2.6 (1.3)	6.3 (0.8)

Appendix A.1 Classroom Objects

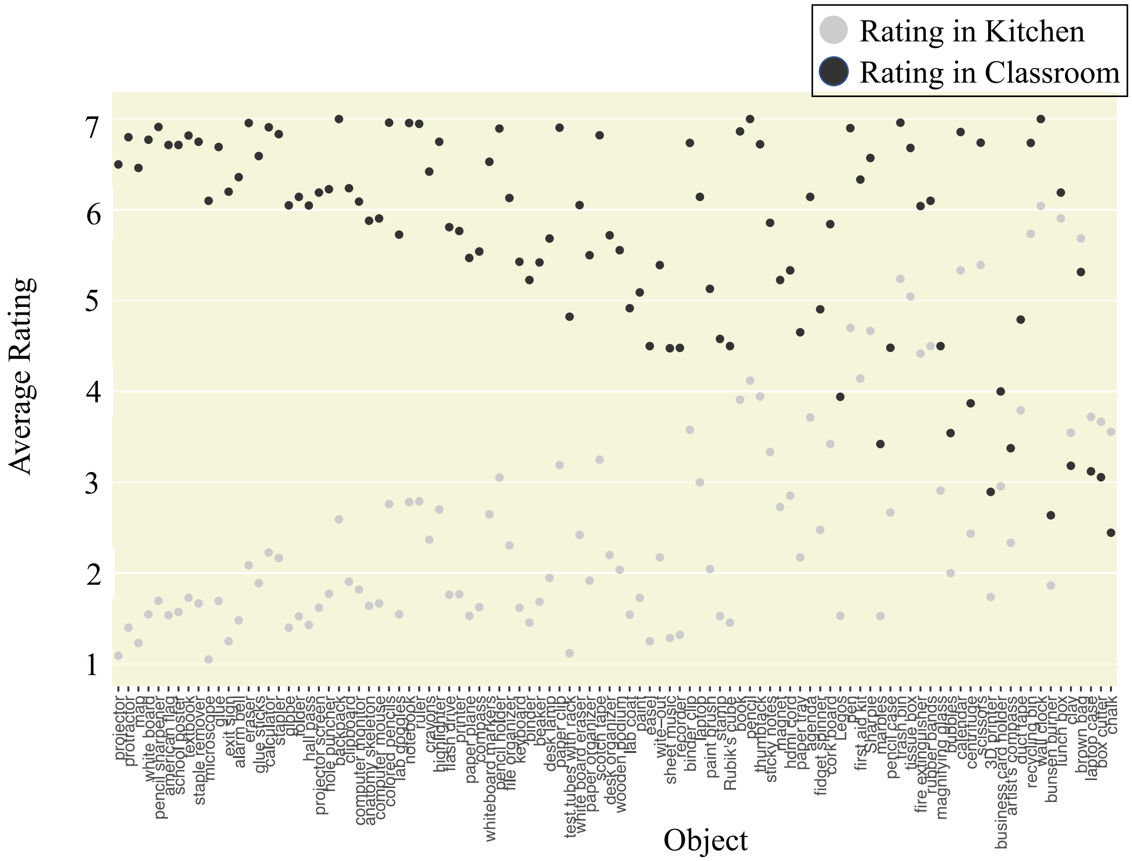

Figure 5 Average ratings of classroom objects. Objects ordered based on difference between ratings in kitchen and classroom.

Appendix A.2 Kitchen Objects

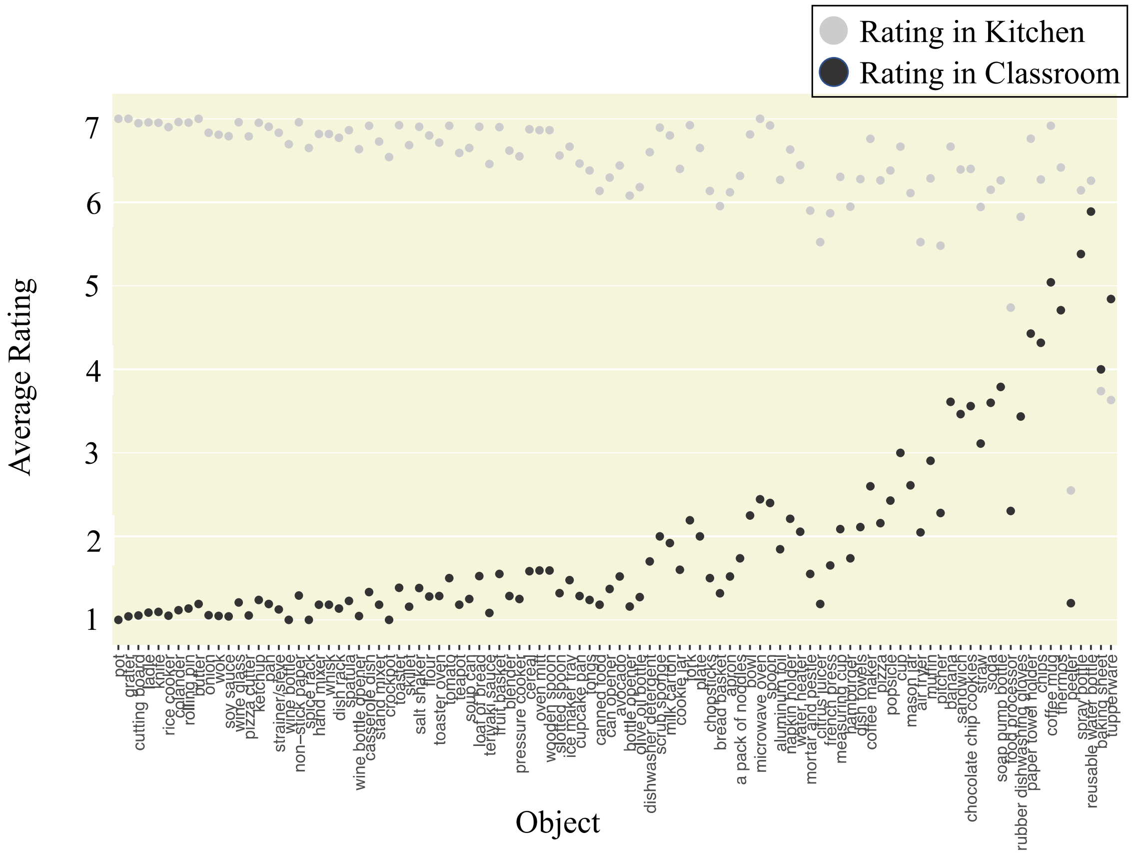

Figure 6 Average ratings of kitchen objects. Objects ordered based on difference between ratings in kitchen and classroom.

Appendix A.3 Miscellaneous Objects

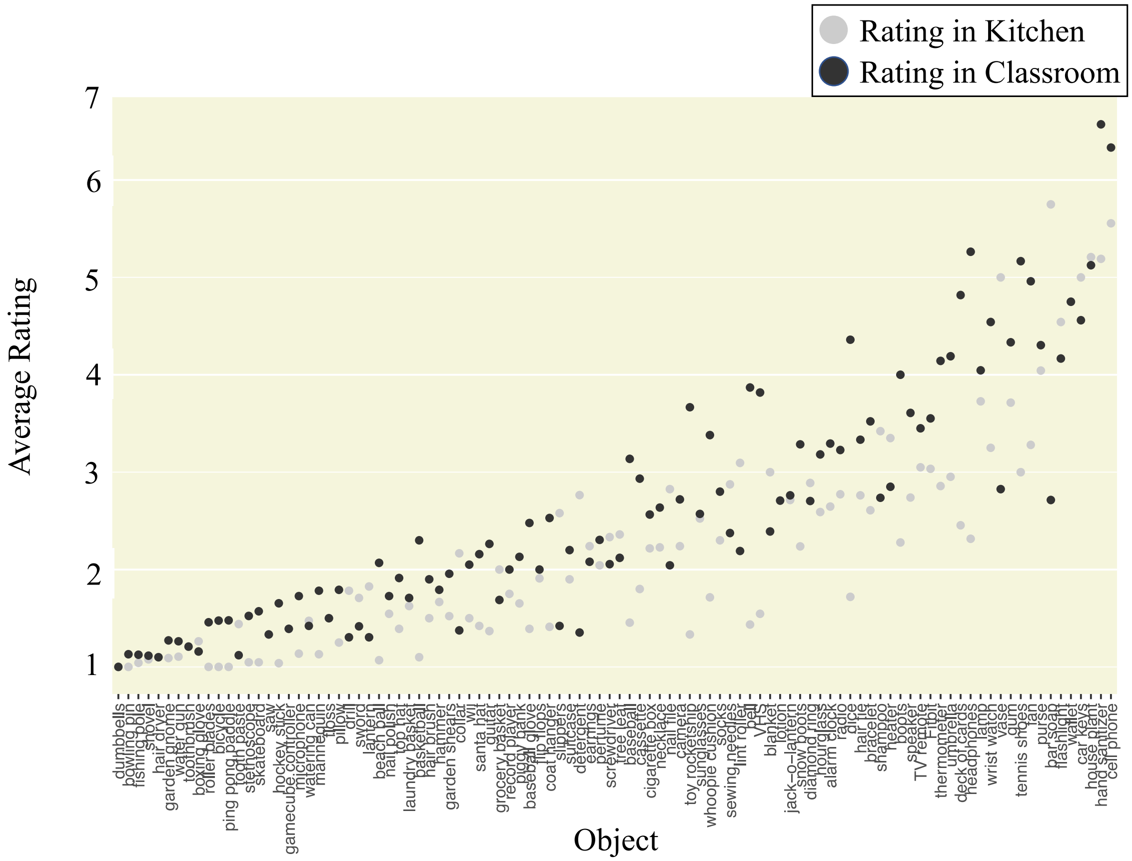

Figure 7 Average ratings of miscellaneous objects. Objects ordered based on sum of ratings in kitchen and classroom.

Appendix B Types of Virtual Objects used in VR Studies

Appendix B.1 Virtual Classroom Objects

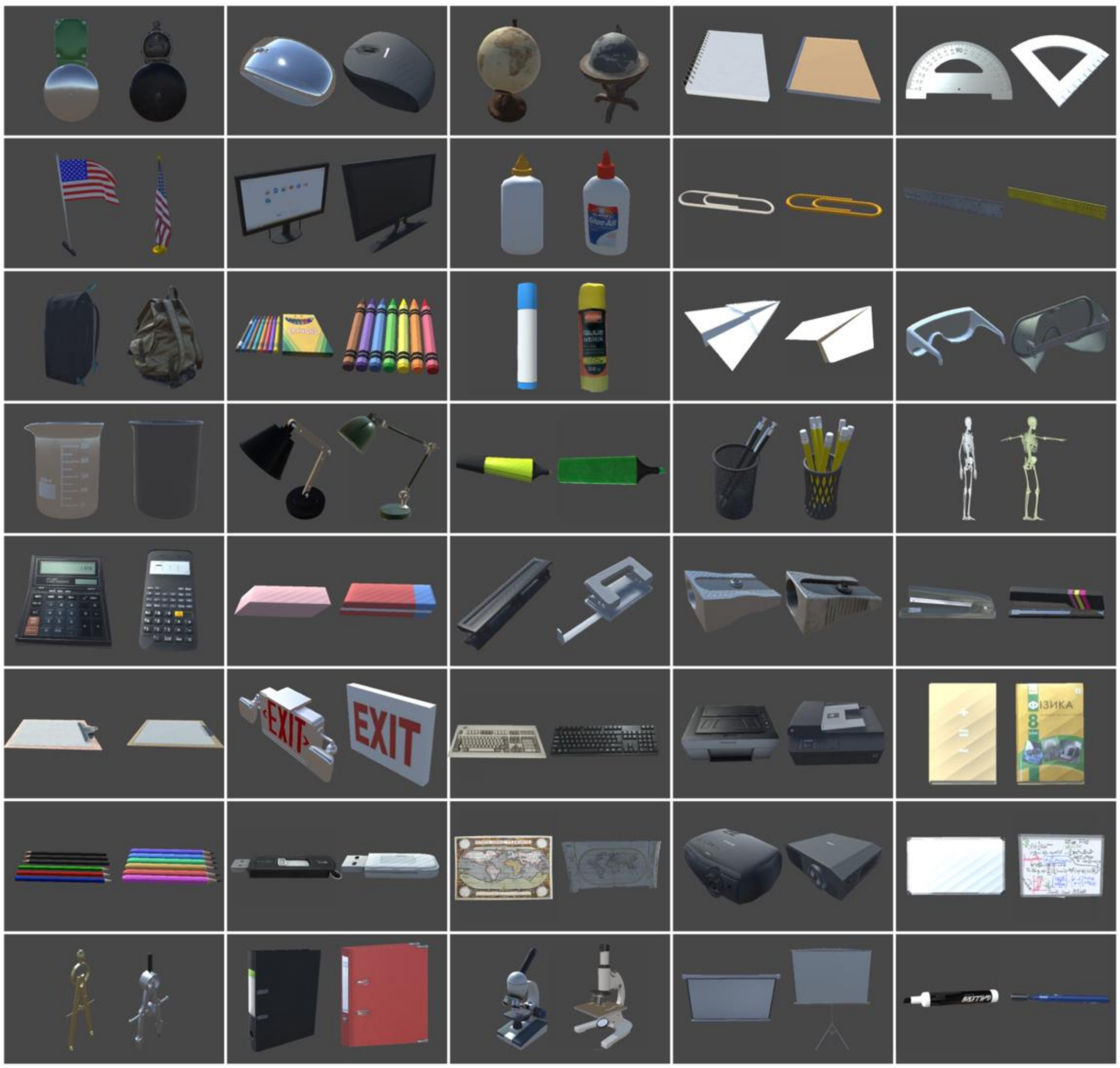

Figure 8 Virtual classroom objects

Table 8 Attributions for objects shown in Figure 8

Title	Author	Source	License
School Alarm Bell	almartin	https://sketchfab.com/3d-models/school-alarm-bell-a8382ca5ce3643d28a92f11deaa5e58e	CC BY 4.0
Alarm	Connections XR	https://sketchfab.com/3d-models/alarm-4aafaccb65be4476b607dff162a1777d	CC BY 4.0
American Flag Pole	Brian Vagie	https://sketchfab.com/3d-models/american-flag-pole-02a63f8e57fd43128ed47da31ae74dba	Standard
Flag of the USA	Wittybacon	https://sketchfab.com/3d-models/flag-of-the-usa-42a30765970747d9af0623885cc07a1b	CC BY 4.0
Backpack	typhomnt	https://sketchfab.com/3d-models/backpack-5655596f9efe47deb09df57a79b44e04	CC BY 4.0
Backpack Photogrammetry	WV_ArtDev	https://sketchfab.com/3d-models/backpack-photogrammetry-b8037798633640e7bf040aac16ea8d45	CC BY 4.0
Beakers	cesar.seidel	https://sketchfab.com/3d-models/beakers-b63ae471653f41e4b327cdcc796fc20c	CC BY 4.0
Chemistry Glassware	maxdragonn	https://sketchfab.com/3d-models/chemistry-glassware-b8594f7dc7e8442dbaaae7a11da4a962	CC BY 4.0
Calculator	black_stone	https://sketchfab.com/3d-models/calculator-7547b73ba9e54c4d89bfa47ba5d6f23f	CC BY 4.0
Casio classwiz calculator	Niilo Poutanen	https://sketchfab.com/3d-models/casio-classwiz-calculator-22ac8280c1434e5f8b41e2fdec45abd6	CC BY 4.0
Clipboard	Cookie	https://sketchfab.com/3d-models/clipboard-a37158f20ccf436483029e8295629738	CC BY 4.0
Clip Board	mengtai	https://sketchfab.com/3d-models/clip-board-a35e2b8adfed472abb572dbac3cff96f	CC BY 4.0
Pencils and Crayons	Šimon Ustal	https://sketchfab.com/3d-models/pencils-and-crayons-47a36071211540a29e0bb9c57da9f478	CC BY 4.0
pensil	Christos77	https://sketchfab.com/3d-models/pensil-92ff4c2b6214443984b4c12ff689e8e6	CC BY 4.0
Drafting Compass	Studio Lab	https://sketchfab.com/3d-models/drafting-compass-b2cc1ab36f5245e5b91e07676c824c17	Standard
Compass drafting	FrancescoMilanese	https://sketchfab.com/3d-models/compass-drafting-a59ab1cd6ea1416bb0aa0e0b1ac431ea	Standard
Computer mouse.	kubassa	https://sketchfab.com/3d-models/computer-mouse-4a6e2b1cf5d54ed5b97da093ed1e74a4	CC BY 4.0
Lowpoly Mouse	khanhnguyen1189	https://sketchfab.com/3d-models/lowpoly-mouse-e0bc8c1d5c8f4be0af37ea852d42d6d9	CC BY 4.0
BenQ Screen	olofunot	https://sketchfab.com/3d-models/benq-screen-5c4457149b9e47a9a118d18e5c8379c7	CC BY 4.0
High Definition Television/Computer Monitor	Glowbox 3D	https://sketchfab.com/3d-models/high-definition-televisioncomputer-monitor-5e384da966574a9a9a337d413dd37b9a	CC BY 4.0
CC0 - Crayons	plaggy	https://sketchfab.com/3d-models/cc0-crayons-22153c3ad0374aaf89ceced9a904283b	CC BY 4.0

Crayons from Poly by Google	IronEqual	https://sketchfab.com/3d-models/crayons-from-poly-by-google-bbd6a669a80b49f0965a569b27d7d5c7	CC BY 4.0
Tomons Desk Lamp	chris	https://sketchfab.com/3d-models/tomons-desk-lamp-cd14b790cb4b47daa9d54422799ca95a	CC BY 4.0
Desk Lamp	olleli1125	https://sketchfab.com/3d-models/desk-lamp-7be9e6cbf6e04365a028217a4874730e	CC BY 4.0
Eraser	chasegianelli	https://sketchfab.com/3d-models/eraser-e596ba5f2ab749b998f42ec33b490c06	CC BY 4.0
Low Poly Eraser	Shenquarh	https://sketchfab.com/3d-models/low-poly-eraser-eb8e47bc0b92455b9722b45e61e94372	CC BY 4.0
Exit Sign	siotech2011	https://sketchfab.com/3d-models/exit-sign-d142e3dcd5c44b5491e6cde6d357e3ce	Standard
Low poly emergency exit sign	Mckai	https://sketchfab.com/3d-models/low-poly-emergency-exit-sign-c722867b5bf5457daf598bb3bc68dd24	CC BY 4.0
Flash Drive	pipotheartist	https://sketchfab.com/3d-models/flash-drive-c13134783bd745c28459a443f3f5ca0c	CC BY 4.0
Flash Drive	Blender3D	https://sketchfab.com/3d-models/flash-drive-ecc57ae0430f4786845a6f76ae924268	CC BY 4.0
Several Folders	janexx	https://sketchfab.com/3d-models/several-folders-1a493b49ef954985ab8057ca66c387d5	CC BY 4.0
Binder	Marcin.Kwiatkowski	https://sketchfab.com/3d-models/binder-78e016eeb0bf45d5bea47547128383a8	CC BY 4.0
Globe	padmadev2005	https://sketchfab.com/3d-models/globe-2d40c8805443463283c1b1547e50e650	CC BY 4.0
Antique Globe	thelowestanimal	https://sketchfab.com/3d-models/antique-globe-a30fc85dd7764b3bb45f509a38c0d000	CC BY 4.0
Glue Bottle	Brutebandit	https://sketchfab.com/3d-models/glue-bottle-bd62c28b8f8146edbea145a347400303	CC BY 4.0
Glue Bottle	stfuaahil	https://sketchfab.com/3d-models/glue-bottle-8f91c8457fec4204a76dad9b5fd9d0df	CC BY 4.0
glue stick	jaisim126	https://sketchfab.com/3d-models/glue-stick-bea25e6e81744af5856abec7b8c9709d	CC BY 4.0
Glue stick	HQ3DMOD	https://sketchfab.com/3d-models/glue-stick-edef5706665c471daf4e255f86f4d105	Standard
Highlighter	c_irby_paint	https://sketchfab.com/3d-models/highlighter-600157f4ffe440f99eb56b08168e1a41	CC BY 4.0
Highlighter with 4K textures	clementdacruz	https://sketchfab.com/3d-models/highlighter-with-4k-textures-5a66e8e4c71d421687c958bc2253b58b	CC BY 4.0
Hole puncher	Double K	https://sketchfab.com/3d-models/hole-puncher-6a654ab63b8a4f6abe8412fa73c3cb91	CC BY 4.0
Hole Puncher	bazz4r	https://sketchfab.com/3d-models/hole-puncher-965804b27d214bf48e1f391bb5035e8e	CC BY 4.0
Computer Mouse And Keyboard	AshMesh	https://sketchfab.com/3d-models/computer-mouse-and-keyboard-2b773750df864e9ea82e8fdbb3af6bb4	Standard
IBM Model M Keyboard	timblewee	https://sketchfab.com/3d-models/ibm-model-m-keyboard-63aec0874c184b53becb74b792588e69	CC BY 4.0

Old world map	Tijerín Art Studio	https://sketchfab.com/3d-models/old-world-map-0ccb0cf0993a4f01968b7a133b22944b	CC BY 4.0
Old World Map	OmegaRedZA	https://sketchfab.com/3d-models/old-world-map-a1a33c127a0b4564888d9db8674d73fb	CC BY 4.0
Microscope	Eugen Vahrushin	https://sketchfab.com/3d-models/microscope-9562226299a045bab13c3d66f8593208	CC BY 4.0
Microscope	Dolores	https://sketchfab.com/3d-models/microscope-9f5942f7c92d49b8a608903c556de37d	CC BY 4.0
Spiral notebook	FrancescoMilanese	https://sketchfab.com/3d-models/spiral-notebook-43abc2c18b014fff9d87b668bacc6f86	Standard
Notebook Prototype	Alexis Diaz	https://sketchfab.com/3d-models/notebook-prototype-70568782312a4729a2b8b03fc1a9ee0f	CC BY 4.0
Paper Clip	Marc Hennessy	https://sketchfab.com/3d-models/paper-clip-96a6be214d2545ac8321da9ba3395bb7	CC BY 4.0
Paper Clips	nro18a	https://sketchfab.com/3d-models/paper-clips-0a38305cab9b44818893ff421b7769fd	CC BY 4.0
Paper Plane	Dominik	https://sketchfab.com/3d-models/paper-plane-6e9201cd4b614d879741ea79524c57c6	CC BY 4.0
Paper Plane	mmateo01	https://sketchfab.com/3d-models/paper-plane-bb63722d8ff64642985507e8d41b0c28	Standard
Wire Mesh Scissor Pen Pencil Holder	3DHaupt	https://sketchfab.com/3d-models/wire-mesh-scissor-pen-pencil-holder-54817471eb5f4c429301cb94db4c6c44	Standard
Pencil Cup and Pencils	swingonaset	https://sketchfab.com/3d-models/pencil-cup-and-pencils-ab58944c22ca474f810ed5d5bf95a0bd	CC BY 4.0
Day#20: Sharpener	JuanG3D	https://sketchfab.com/3d-models/day20-sharpener-520e43463f7c4f4f8be96f8ff9986b0e	CC BY 4.0
The pencil sharpener	Artieee	https://sketchfab.com/3d-models/the-pencil-sharpener-f96cb11297ee4c29948f2f6823c1b2cd	CC BY 4.0
Printer- Low Poly	CG Buzz	https://sketchfab.com/3d-models/printer-low-poly-8a3a68f84f4d4a34973b527875a7314b	CC BY 4.0
Inkjet printer and scanner	1-3D.com	https://sketchfab.com/3d-models/inkjet-printer-and-scanner-ecb6f40c66ff4307a3eadb67cabc83dc	CC BY-SA 4.0
Projector Set	comphonia	https://sketchfab.com/3d-models/projector-set-18428ceaffee47f5b9e90219adbfbefd	CC BY 4.0
Video projector	1-3D.com	https://sketchfab.com/3d-models/video-projector-e14a2b9336df47a6b536a3a1cf829221	CC BY-SA 4.0
Projector Set	comphonia	https://sketchfab.com/3d-models/projector-set-18428ceaffee47f5b9e90219adbfbefd	CC BY 4.0
Projection canvas	FrancescoMilanese	https://sketchfab.com/3d-models/projection-canvas-f229fccca0654f5689231bbb42d5e896	Standard
Protractor	FrancescoMilanese	https://sketchfab.com/3d-models/protractor-4f0a1d50bba941a59e1bea73f547baf6	Standard
Protractor	Microsoft	https://sketchfab.com/3d-models/protractor-3de4bcf1dece4f348f6757e77e5c55c7	CC BY 4.0
JDi-Ruler	JDi Design	https://sketchfab.com/3d-models/jdi-ruler-2e82fdebaf8f449e979b56b260543ffb	CC BY 4.0

Ruler	Connections XR	https://sketchfab.com/3d-models/ruler-db1883e2b2e04edfba72fa35751a7694	CC BY 4.0
Safety Goggles	bariacg	https://sketchfab.com/3d-models/safety-goggles-0cb8490545114c72b1c7700ef4215451	Standard
Eye protection glasses	vinigor	https://sketchfab.com/3d-models/eye-protection-glasses-0ba6c4545fe14f0d9b8406ff030fd042	CC BY 4.0
Skeleton	Diego Luján García	https://sketchfab.com/3d-models/skeleton-4de7b96a351a4a35b1b6e5415277ff07	CC BY 4.0
Human skeleton	aplanva	https://sketchfab.com/3d-models/human-skeleton-23a06a148f9145769e822e74fe6b72fc	CC BY 4.0
Vintage stapler	viveleroi	https://sketchfab.com/3d-models/vintage-stapler-f15c7f6fbf7d4c4a88217b32dfd39eec	CC BY 4.0
Stapler	Henry VIII	https://sketchfab.com/3d-models/stapler-eb02cd20aafd4e21bc1a5f3252e8a914	CC BY 4.0
Textbook from Poly by Google	IronEqual	https://sketchfab.com/3d-models/textbook-from-poly-by-google-8dec4845fbc74193a30beac39c8a89c8	CC BY 4.0
Physics Book	fchaolshi	https://sketchfab.com/3d-models/physics-book-2a89aaa64c974231a48bea839a21c879	CC BY 4.0
Whiteboard	Reflex_Entertainment	https://sketchfab.com/3d-models/whiteboard-eff6059c0f654aa3a5ba5e10eb59591e	CC BY 4.0
Whiteboard	marlenegrol313	https://sketchfab.com/3d-models/whiteboard-999f7b6bb4a44a6e933aeb59e68c38ef	CC BY 4.0
Dry Erase Whiteboard Marker	maqfab	https://sketchfab.com/3d-models/dry-erase-whiteboard-marker-59afa34850534eb1a2368001795fc671	CC BY 4.0
Berol Whiteboard Marker	Muhammad Rahman	https://sketchfab.com/3d-models/berol-whiteboard-marker-b66dd1d68d4a4afeabbb71065e7ba526	CC BY 4.0

Note. Standard refers to Sketchfab Standard License.

Appendix B.2 Virtual Kitchen Objects

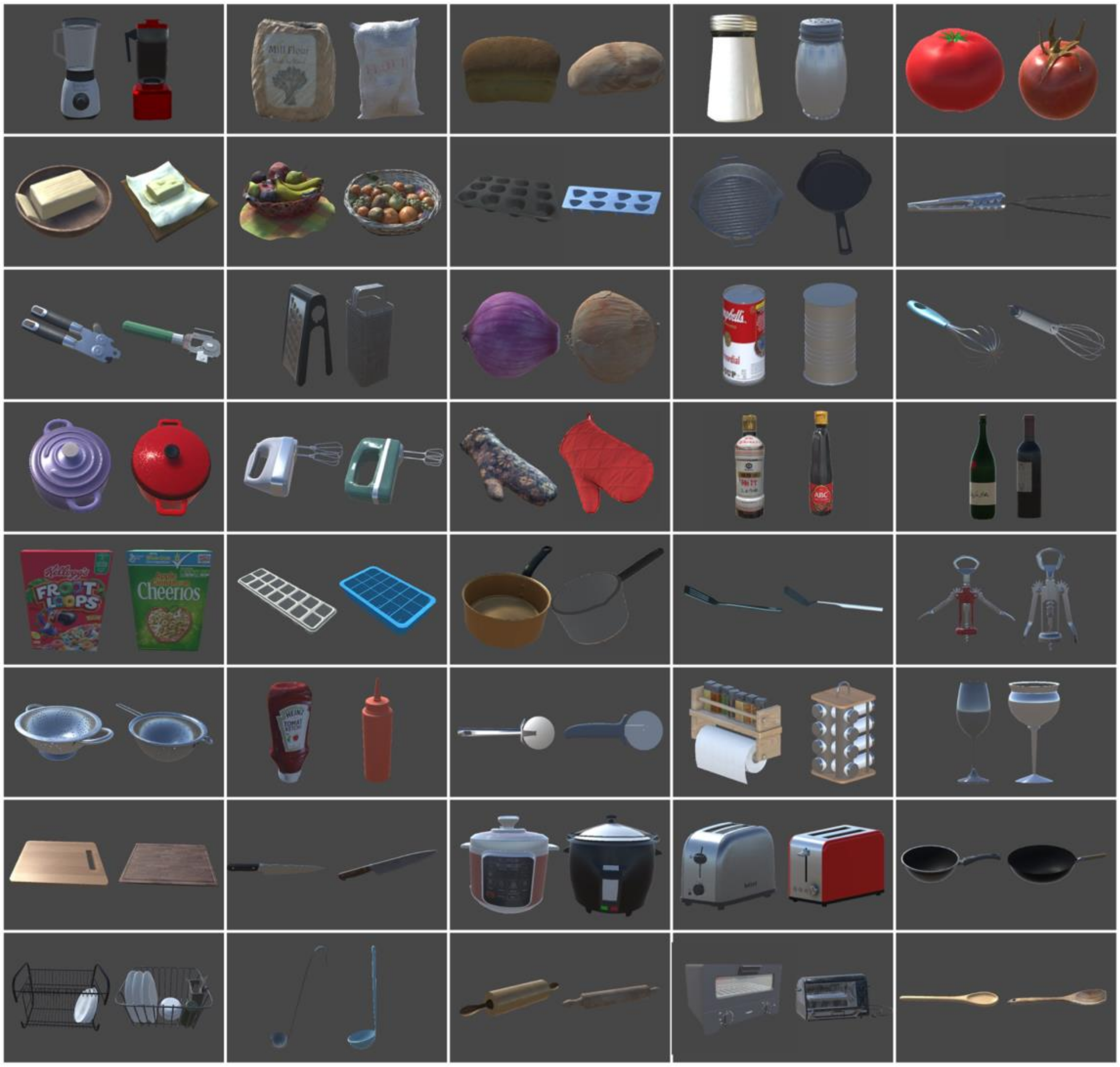

Figure 9 Virtual kitchen objects

Table 9 Attributions for objects shown in Figure 9

Title	Author	Source	License
Kitchen Blender	AirStudios	https://sketchfab.com/3d-models/kitchen-blender-3a9c105e31734187b2fa37b7759f050a	Standard
Blender	Márcio Nunes	https://sketchfab.com/3d-models/blender-8956ca6f34b741e3a8b3ed059b54c196	CC BY 4.0
Butter_Dish_FBX	GetDeadEntertainment	https://sketchfab.com/3d-models/butter-dish-fbx-98a1c09021c0418c98e83ae2e82e3fe5	Standard
PB121 Butter Low	Makovetkyi Volodymyr	https://sketchfab.com/3d-models/pb121-butter-low-4db1f5be40844a5a8127c4db42c28424	CC BY 4.0
Can Opener	hectopod	https://sketchfab.com/3d-models/can-opener-4425ee6c9b7948ea872ed75beb66aaf1	CC BY 4.0
Can Opener	graygabriel	https://sketchfab.com/3d-models/can-opener-8237129bfae244d7a62d706937f9f106	CC BY 4.0
Le Creuset Style Dish	phillips.kieran	https://sketchfab.com/3d-models/le-creuset-style-dish-8877fc9e7fea4c4d91cc80fae457fd45	CC BY 4.0
Casserole dish	Pledg	https://sketchfab.com/3d-models/casserole-dish-dfa8bbb1d7024ae7b46147dbd03d66e0	Standard
Cereal Model	BaconMaster	https://sketchfab.com/3d-models/cereal-model-9f05f77c60f442a982153faf09dcb75e	CC BY 4.0
Cerealbox	gomelchuck	https://sketchfab.com/3d-models/cerealbox-3b9bcc1ee0554005851edb53ea7d56cd	CC BY 4.0
Colander	Axeonalias	https://sketchfab.com/3d-models/colander-f346c78a2c6e463b8204ae68498e5584	Standard
Stainless Steel Colander PBR	romullus	https://sketchfab.com/3d-models/stainless-steel-colander-pbr-325925d721ab4f45b3c49707fb445466	Standard
Cutting Board	Diccbudd	https://sketchfab.com/3d-models/cutting-board-ce34c8bf389d4053aae98b9d2752a7b9	CC BY 4.0
Simple Cutting Board (Kitchen Collection)	PrimaVodka	https://sketchfab.com/3d-models/simple-cutting-board-kitchen-collection-47c554254fd24ac29966e71819c2a0be	CC BY 4.0
dish rack	prasetyoheru10	https://sketchfab.com/3d-models/dish-rack-f446a5fcb70c403587619929f883e2b1	CC BY 4.0
Dish Rack with Dishes	HippoStance	https://sketchfab.com/3d-models/dish-rack-with-dishes-ce69014964624fbb808a028e5c55d88b	CC BY 4.0
Flourbag	Thunder	https://sketchfab.com/3d-models/flourbag-837e441c984e4da5a12d114f82d9acd6	CC BY-SA 4.0
Prop Project [Texture Map]: Flour Bag	aishwarya811	https://sketchfab.com/3d-models/prop-project-texture-map-flour-bag-0aa4687566bd45c1821788ed267452cb	CC BY 4.0
Fruit Decay	Moshe Caine	https://sketchfab.com/3d-models/fruit-decay-743de6a371b04c7993e3c263e04cfc06	CC BY 4.0
F001 Fruits	bimage	https://sketchfab.com/3d-models/f001-fruits-572492669b514fd19d1e7a3d803145ad	CC BY 4.0

Grater	BlinFriend	https://sketchfab.com/3d-models/grater-f145fb35b74d4d95b9dcf914795dda45	CC BY 4.0
Freebie - Game Art: Graters	Alex Filip	https://sketchfab.com/3d-models/freebie-game-art-graters-56443d7c135049d69662efe018aac97f	CC BY 4.0
Hand Mixer	assetfactory	https://sketchfab.com/3d-models/hand-mixer-ec0d859b225a41fba8881a2e71b7fc30	Standard
Electric mixer	leonsavelind	https://sketchfab.com/3d-models/electric-mixer-e6718e5f0b684d399bb7cbe46f7b4840	CC BY 4.0
ICE CUBE TRAY - VASCHETTA GHIACCIO	Meshes3D	https://sketchfab.com/3d-models/ice-cube-tray-vaschetta-ghiaccio-41e0d274dac84a1c9304e176397e055e	CC BY 4.0
Ice cube tray from Poly by Google	IronEqual	https://sketchfab.com/3d-models/ice-cube-tray-from-poly-by-google-00ed9ab3393f4f8daf9de1687d9abf69	CC BY 4.0
Ketch Up	rogerpest	https://sketchfab.com/3d-models/ketch-up-f96a4fb0b5f44219afe401c72ac4d6dd	CC BY 4.0
Ketchup Bottle low poly	SusanKing	https://sketchfab.com/3d-models/ketchup-bottle-low-poly-aa840004cd12489daf8d8f5ca0fef013	CC BY 4.0
Kitchen Knife	TheSpacePunk	https://sketchfab.com/3d-models/kitchen-knife-4c75aae7dfa74b919b61a321242de7f4	CC BY 4.0
Big Knife	Nathalie Michel	https://sketchfab.com/3d-models/big-knife-46b2c1d289f448be8d5562b10ad7f55c	CC BY 4.0
Ladle	Lightningx	https://sketchfab.com/3d-models/ladle-3c1fe2f2c77b4d258c3d1a08de55eb1a	CC BY 4.0
Ladle △952	O-tolab	https://sketchfab.com/3d-models/ladle-952-ce27e3369587476c85a436905f1e5c00	CC0 1.0
Bread Loaf scan	John Fino (tauricity)	https://sketchfab.com/3d-models/bread-loaf-scan-69569b663c3245afa2a14209e9c665d5	CC BY-SA 4.0
Loaf of Bread	Meerschaum Digital	https://sketchfab.com/3d-models/loaf-of-bread-c68c30014fc54888b3ba0eb17fa46414	CC BY 4.0
Anodized Aluminium Muffin Pan Model	Gregory Allen Brown	https://sketchfab.com/3d-models/anodized-aluminium-muffin-pan-model-47b6658229314c3f8a1c7b9c0a153c41	Standard
Sea of Galilee Muffin Pan	321Blender	https://sketchfab.com/3d-models/sea-of-galilee-muffin-pan-114e68ed03b946e69c4a47ec12ea22e7	CC BY 4.0
Purple Onion	mjk	https://sketchfab.com/3d-models/purple-onion-70fdef1abc1744e3a3e0a828d6821fbf	CC BY 4.0
Onion(3d Scan)	tanophotogrammetry	https://sketchfab.com/3d-models/onion3d-scan-bac0ceef416c4ef88750f659f3bca592	CC BY 4.0
Floral Oven Mitt	Marc Sawyer	https://sketchfab.com/3d-models/floral-oven-mitt-71710fbfb90d456682c35f5ef8777de6	Standard
Cooking Hot Handle Oven Gloves	3dia	https://sketchfab.com/3d-models/cooking-hot-handle-oven-gloves-83ad6e2bf7934fe3bacb67e76d4f3277	Standard

CC0 - Pan 3	plaggy	https://sketchfab.com/3d-models/cc0-pan-3-cba4bcda468540c7a3ff843b08f22412?cursor=bz00JnA9Mw%3D%3D	CC0 1.0
Saucepan	Neepsy	https://sketchfab.com/3d-models/saucepan-22a568374d8b4fad881c1d3970f61bb8	CC BY 4.0
Pizza Cutter / ピザカッター	O-tolab	https://sketchfab.com/3d-models/pizza-cutter-ccd89c4ee1ba45afa778d1cac8a5cc9f	CC0 1.0
Pizza cutter from Poly by Google	IronEqual	https://sketchfab.com/3d-models/pizza-cutter-from-poly-by-google-d47126df65774fce96bf3b6072f042eb	CC BY 4.0
supor Rice cooker 苏泊尔电饭锅	jiuyue	https://sketchfab.com/3d-models/supor-rice-cooker-a9bf09f4f333493580d75b4bde98f9cb	CC BY 4.0
Rice Cooker	AyunFat	https://sketchfab.com/3d-models/rice-cooker-3f70c8b7cf704bdb952e09c0d5f5ab65	CC BY 4.0
Rolling pin low poly	SusanKing	https://sketchfab.com/3d-models/rolling-pin-low-poly-3ba7bdf33bd14f7695b1b5932b9cf769	CC BY 4.0
Wooden Rolling Pin	GameDev Nick	https://sketchfab.com/3d-models/wooden-rolling-pin-e5d077535f1241d39121d5c87c65bfaa	CC BY 4.0
Salt and pepper 3	FrancescoMilanese	https://sketchfab.com/3d-models/salt-and-pepper-3-198a880ab1d44616a06f15fe18029948	Standard
Salt And Pepper Shakers	Yanez Designs	https://sketchfab.com/3d-models/salt-and-pepper-shakers-5f2adebdda754e40915d1330a61fa70c	CC BY 4.0
skillet steel	meminbiyikli	https://sketchfab.com/3d-models/skillet-steel-83d6defd33734f2da2d81ddc036aa8df	CC BY 4.0
Cast Iron Skillet	pityafinwe	https://sketchfab.com/3d-models/cast-iron-skillet-52a8cf585c3a409b94030d109a098da8	CC BY 4.0
Can Soup	Yanez Designs	https://sketchfab.com/3d-models/can-soup-6f2309ef36b34a7686cb62de0e2dd005	CC BY 4.0
Soup Can	knight_of_the_flame	https://sketchfab.com/3d-models/soup-can-1a67ade7bce34c0ba785f9544d460dfc	CC BY 4.0
Soy Sauce	MOL	https://sketchfab.com/3d-models/soy-sauce-68e16629671748b89199c7ad88d5ca99	CC BY 4.0
Soy Sauce Scan	Dawnstar-Chronicles	https://sketchfab.com/3d-models/soy-sauce-scan-6af949a656254e18bf5eff31c4af7853	CC BY 4.0
Slotted Turner △901	O-tolab	https://sketchfab.com/3d-models/slotted-turner-901-81b129ecf5724f63b5b044702a3140c2	CC0 1.0
Spatula from Poly by Google	IronEqual	https://sketchfab.com/3d-models/spatula-from-poly-by-google-a67a1d7f346d4e1ea7b39774663657a3	CC BY 4.0
Paper Towel Rack with Spices | Game Assets	PropDrop	https://sketchfab.com/3d-models/paper-towel-rack-with-spices-game-assets-2cbe61751a90424c93de8ea9ad4c0dd1	Standard
Spice rack	gorzi	https://sketchfab.com/3d-models/spice-rack-14f0d2c353b04cbc84a93005e67381e9	CC BY 4.0
Toaster	Artem P	https://sketchfab.com/3d-models/toaster-0dd620043178479db6752ab103b1e04e	CC BY 4.0

toaster	CG_alone	https://sketchfab.com/3d-models/toaster-d35d4c4065494d1687d06aa7353f6d79	CC BY 4.0
Daily Oven Toaster	interior model	https://sketchfab.com/3d-models/daily-oven-toaster-02019b633f454b8e94002f2020308be0	Standard
Old Oven Toaster Grill (OTG)	Alphamesh	https://sketchfab.com/3d-models/old-oven-toaster-grill-otg-37172f9d07d44f8ca91d8b9ba600aa46	Standard
Tomato	MrPuppet	https://sketchfab.com/3d-models/tomato-526463de7cc4491c8bc3cd158811ab4e	CC BY 4.0
Tomato 2	Moshe Caine	https://sketchfab.com/3d-models/tomato-2-201d42a9e5e54f1b836eff39a892ed88	CC BY 4.0
Tongs	AtandMi	https://sketchfab.com/3d-models/tongs-74f71d92c648446a8b9f4089bb440f4e	CC BY 4.0
Kitchen 5-piece utensil set	HQ3DMOD	https://sketchfab.com/3d-models/kitchen-5-piece-utensil-set-c122a94ab1994f0186093c6a7eff0e79	Standard
Whisk △950	O-tolab	https://sketchfab.com/3d-models/whisk-950-990d0cb9499540fda49b1ff36be9ba26	CC0 1.0
Whisk	Unknown_user999	https://sketchfab.com/3d-models/whisk-a40a85839fa846b0a1b750f4dfb365a5	CC BY 4.0
Wine Bottle	Reeeeeece	https://sketchfab.com/3d-models/wine-bottle-44fb75db4f5641deae1425d220d5eba9	CC BY 4.0
Wine Bottle	aya.albayati	https://sketchfab.com/3d-models/wine-bottle-f2593afa7d63416a8acf4abe8fcbfcf7	CC BY 4.0
CorckScrew Openner	Francesco Coldesina	https://sketchfab.com/3d-models/corckscrew-openner-f9f04b1dced743538da941e49a56b046	CC BY 4.0
Winged Corkscrew (Animation)	jashanchopra	https://sketchfab.com/3d-models/winged-corkscrew-animation-21ddf470a3fe4095a0ef58778e897187	CC BY 4.0
Wine glass	laanita	https://sketchfab.com/3d-models/wine-glass-88c1cc6d02fb49cfa35692b790134594	CC BY 4.0
Fine Wine Glass	Allison Simonette	https://sketchfab.com/3d-models/fine-wine-glass-55305f6a763d47b6b8c6a5896eed98c7	CC BY 4.0
Wok_Homework 10	Citflo	https://sketchfab.com/3d-models/wok-homework10-c268b7cb334b4d2a8ccfaad3219603b3	CC BY 4.0
Cooking Wok 4k	PhotoGramGear	https://sketchfab.com/3d-models/cooking-wok-4k-bc689633948c43248ab3cb2bfe8b017b	Standard
Wooden spoon	quedlin	https://sketchfab.com/3d-models/wooden-spoon-2cdb7b9b398244ccbf887aeb1cde8328	CC BY 4.0
Wooden Spoon	Reifer	https://sketchfab.com/3d-models/wooden-spoon-2613c5f24bb3407da2664c410c34d523	CC BY 4.0

Note. Standard refers to Sketchfab Standard License.

Appendix B.3 Virtual Miscellaneous Objects

Figure 10 Virtual miscellaneous objects

Table 10 Attributions for objects shown in Figure 10

Title	Author	Source	License
Basketball	Scott VanArsdale	https://sketchfab.com/3d-models/basketball-e3c719662981472f8479031a074bc727	CC BY 4.0
Wilson Basketball	Ika3D	https://sketchfab.com/3d-models/wilson-basketball-0bd35aa0fe4a44b9afab1ac4c72e091e	CC BY 4.0
beach ball	HQ3DMOD	https://sketchfab.com/3d-models/beach-ball-8ed7f688d9b4441e931c45545043cd6e	CC BY 4.0
Oculus Beach Ball	tg	https://sketchfab.com/3d-models/oculus-beach-ball-0fc69683beb74e6e87853e412d7ffe32	CC BY 4.0
Bicycle	Klaas Nienhuis	https://sketchfab.com/3d-models/bicycle-4saPxqRTOLETE9TlL5iZkKd9zI1	CC BY 4.0
Bicycle ^^	pot4tochip	https://sketchfab.com/3d-models/bicycle-467c6873188044ee85066fa3cea957f5	CC BY 4.0
Pino de boliche / bowling pin	RafaeoAchaque	https://sketchfab.com/3d-models/pino-de-boliche-bowling-pin-794291f457b6415585d17ae2f0a22f58	CC BY 4.0
Bowling Pin	Connections XR	https://sketchfab.com/3d-models/bowling-pin-007b32a30e1d4f438a7f7c73421afbdb	CC BY 4.0
Challenger boxing glove	alban	https://sketchfab.com/3d-models/challenger-boxing-glove-b9b8b6aebfd146b8a11f840b2f8d0cca	CC BY 4.0
Boxing Glove	Santa Cruz Museum of Art and History	https://sketchfab.com/3d-models/boxing-glove-978bdcc429f840a6a7ee94a44217556e	CC BY 4.0
Pet collar	Skaði	https://sketchfab.com/3d-models/pet-collar-3592fc56b4ff41d4819b75e4e917e938	CC BY 4.0
Cat_Collar_Mesh	Flumpinator	https://sketchfab.com/3d-models/cat-collar-mesh-4efdc98ca25d4a849ee97742eca40123	CC BY 4.0
Simple Power Drill	coleminerman	https://sketchfab.com/3d-models/simple-power-drill-da309385cf004c469f89cf4f0267f796	CC BY 4.0
Drill Retopo	Francesco Coldesina	https://sketchfab.com/3d-models/drill-retopo-8fd5608b449f4cde81a8d924cdaed416	CC BY 4.0
iron Dumbel	giga	https://sketchfab.com/3d-models/iron-dumbel-f5ccda1a705a4f68a360060bb69219c2	CC BY 4.0
Dumbbell	RoutineStudio	https://sketchfab.com/3d-models/dumbbell-60d1d4b3fb494bfb971a920f16187b2b	CC BY 4.0
Stylized Fishing Rod	Coco Jinjo	https://sketchfab.com/3d-models/stylized-fishing-rod-9762871f658a4e1f879c3a7fb241dd68	Standard
Fishing rod	LinNacume	https://sketchfab.com/3d-models/fishing-rod-2cf6b1c0e8c34e0f82b11ffaff0b80b5	CC BY 4.0
Personal Care Section	Marc Wheeler	https://sketchfab.com/3d-models/personal-care-section-5f9d43cd7863491094bbd63ae1a81856	Standard
Dental Floss - Mint	Marc Wheeler	https://sketchfab.com/3d-models/dental-floss-mint-4d1f533f79a44ebe9fce8bc52c047e4a	Standard
Gamecube Controller	CoryRichards	https://sketchfab.com/3d-models/gamecube-controller-21983501bac64993ac09cdc7936ffdf2	CC BY 4.0

Gamecube Controller Retopo	twr2404	https://sketchfab.com/3d-models/gamecube-controller-retopo-da57abaedb37414c8071982d8562009b	CC BY 4.0
Mesh Garden Gnome	Seth Berrier	https://sketchfab.com/3d-models/mesh-garden-gnome-e2d712be51ea436588651802e51340c6	CC BY 4.0
High Fidelity Garden Gnome	caitlyn	https://sketchfab.com/3d-models/high-fidelity-garden-gnome-2512c6b3e5724d298428decd0f812be8	CC BY 4.0
Hedge Shears	Ed+	https://sketchfab.com/3d-models/hedge-shears-3e6e54a34410465988515400aba29954	Standard
Shears - GAP Assignment	Camille Leclercq	https://sketchfab.com/3d-models/shears-gap-assignment-c05eb5b2c53747698e8bf920d8025b07	CC BY 4.0
ibanez jem guitar	abazibiz	https://sketchfab.com/3d-models/ibanez-jem-guitar-daeadd913644438aa3096bb357a02016	CC BY 4.0
Guitar	ironcladmax501	https://sketchfab.com/3d-models/guitar-7ab6e59ba93b46bd8afa981fef92f114	CC BY 4.0
Hairbrush	Massimiliano Castiglione	https://sketchfab.com/3d-models/hairbrush-1fb36a3766074456bbb67cec452fbdbb	CC BY 4.0
FREE Hair Brush CC0	adadadad5252341	https://sketchfab.com/3d-models/free-hair-brush-cc0-6da221933be543948c894ba53108e624	CC BY 4.0
Hair Dryer Philips	BlackFenix_URS	https://sketchfab.com/3d-models/hair-dryer-philips-8a2ffb84162a4af2ba3a6560d10bafce	CC BY 4.0
80's Hair Dryer	ukocabay	https://sketchfab.com/3d-models/80s-hair-dryer-245892bf032442d3bcd306158510c9b8	CC BY 4.0
Hammer	Denis Zapadenko	https://sketchfab.com/3d-models/hammer-b1682f7b087c474ab811e4cc88426aec	CC BY 4.0
Bloody Hammer	Gargore	https://sketchfab.com/3d-models/bloody-hammer-b9d32f87c73f48659ccd9bf75f7dc66c	Standard
Wooden Hockey Stick	Ed+	https://sketchfab.com/3d-models/wooden-hockey-stick-d6aeb829e02f4937b4d55332c7e5c95e	Standard
Hockey Stick	Duznot	https://sketchfab.com/3d-models/hockey-stick-3f6b365520474d6c8353b40afece41dd	CC BY 4.0
Lantern	Gwappa	https://sketchfab.com/3d-models/lantern-cda18f4050cb4bd68d63abe7c77a771e	CC BY 4.0
Lantern Model	adraude_12	https://sketchfab.com/3d-models/lantern-model-a90eb130d5d4499194277f00e143dc7c	CC BY 4.0
Laundry Basket	ÆON	https://sketchfab.com/3d-models/laundry-basket-b15df49240f648039dc95fc4eb0d6f4a	Standard
Laundry Basket	fatihmcnn	https://sketchfab.com/3d-models/laundry-basket-b6aa6e7f91d545f3bb5d4027a83e2da1	CC BY 4.0
Wig Mannequin	Jacob.Elhatmi	https://sketchfab.com/3d-models/wig-mannequin-63b3a3b35e9242d2b914064af26bf7fe	CC BY 4.0
Female Mannequin Head	Kitamago	https://sketchfab.com/3d-models/female-mannequin-head-35eba64bcfd54e7da8fc387f0ae052df	Standard

Microphone	Aike	https://sketchfab.com/3d-models/microphone-cf9580db004e4bd6818306d50f2fa2ce	CC BY 4.0
Wireless Microphone	CARTE 3D	https://sketchfab.com/3d-models/wireless-microphone-1f48a1a02fa448e5b9b2f350f05a401d	CC BY 4.0
Pink nail polish	turtlemode	https://sketchfab.com/3d-models/pink-nail-polish-b416f0e0fdfd4e9e9ea8f371e5661d6c	CC BY 4.0
Nailpolish Lowpoly	maja	https://sketchfab.com/3d-models/nailpolish-lowpoly-3acced4fd45a4dcc831dbbf842669974	CC BY 4.0
Piggy Bank	octopuslover	https://sketchfab.com/3d-models/piggy-bank-4d5bf8d42f2d4c3493dc13a168944d64	CC BY-SA 4.0
Piggy Bank	Tomas Rubianes	https://sketchfab.com/3d-models/piggy-bank-1ee1268a508c40b28b1e7c734ba583ec	CC BY 4.0
Pillow	3DMish	https://sketchfab.com/3d-models/pillow-28cf19822d954753a9173ebc09f77cf3	CC BY 4.0
Pillow, cushion	SusanKing	https://sketchfab.com/3d-models/pillow-cushion-47a08beda8ae415fa22f27087cc499cd	CC BY 4.0
Ping pong Paddle scanned with ACADEMIA 50	Creaform 3D	https://sketchfab.com/3d-models/ping-pong-paddle-scanned-with-academia-50-43565fda2deb470fbe86e5561a2e1e4e	CC BY 4.0
Old Table Tennis Racket	LNTH	https://sketchfab.com/3d-models/old-table-tennis-racket-e47279f54dde446baab49bbd6cc3ac0d	Standard
Yamaha TT-300 Record Player	AleixoAlonso	https://sketchfab.com/3d-models/yamaha-tt-300-record-player-3577a2a1a0c24218bd5d768beccf218e	CC BY 4.0
Record Player	Rick (WeaZy)	https://sketchfab.com/3d-models/record-player-de1283e3b23a4fd5aa2e9932c78eba39	CC BY 4.0
Quads roller skates	Vladislav Fedulov	https://sketchfab.com/3d-models/quads-roller-skates-ae894484675a492ba11554a24e063bdb	CC BY 4.0
70's - 80's Roller Skate	gozdemrl	https://sketchfab.com/3d-models/70s-80s-roller-skate-c4950486ca6a43efad88aa3787383064	CC BY 4.0
Santa Hat	3d-Pauer	https://sketchfab.com/3d-models/santa-hat-73e47e8d858f4d5992508da5987951b2	CC BY 4.0
Christmas Hat	Shedmon	https://sketchfab.com/3d-models/christmas-hat-b44d66b16ba543c9825af6f95bd3d678	CC BY 4.0
Saw	billycorveleyn	https://sketchfab.com/3d-models/saw-a1274c875aa249c58c39d667683eb061	CC BY 4.0
Saw Tool	TraianDumbrava	https://sketchfab.com/3d-models/saw-tool-daff4bc1ecf14d43af365839d727a2f0	CC BY 4.0
Dirty Shovel	tediuminteractive	https://sketchfab.com/3d-models/dirty-shovel-7cf472435d454bbcad276fa4fc7ca832	CC BY 4.0
Shovel	Oleksandr Pelypenko	https://sketchfab.com/3d-models/shovel-ffa191ffe355485487b6231970c81ace	Standard
Skateboard	Johnson Martin	https://sketchfab.com/3d-models/skateboard-4b0f217a8b9043b781f23a271ceb2276	CC BY 4.0
Wood Penny Skateboard	natmr	https://sketchfab.com/3d-models/wood-penny-skateboard-618044c27b3040ae8bea4e38b3e9555f	CC BY 4.0

Stethoscope	Phillip Stephens	https://sketchfab.com/3d-models/stethoscope-ce1ba77195dd4746841e58346864c059	CC BY 4.0
Stethoscope low poly 3d model Free download	zack424	https://sketchfab.com/3d-models/stethoscope-low-poly-3d-model-free-download-1971543980c8432686c80fd41b5e7f12	CC BY 4.0
Fantasy_sword_26_with_scabbard	Nicu_Tepes_Vulpe	https://sketchfab.com/3d-models/fantasy-sword-26-with-scabbard-17143317c8904bfa8f2a142ca6eaf5ee	Standard
medieval sword	LowSeb	https://sketchfab.com/3d-models/medieval-sword-da574cba504e4b83a3293f3d3bd067fb	CC BY 4.0
Toothbrush	charlesmconard	https://sketchfab.com/3d-models/toothbrush-3d334e0398ce44a598573a819e0daa79	CC BY 4.0
Toothbrush	Emanuel Silva	https://sketchfab.com/3d-models/toothbrush-89307364580948418 6efa98c248d8efc	CC BY 4.0
colgate toothpaste tube	Starkster	https://sketchfab.com/3d-models/colgate-toothpaste-tube-3a77c506eaea4e08a10f1d288d2ce45d	CC BY 4.0
Toothpaste	ajyotimahanta	https://sketchfab.com/3d-models/toothpaste-4fb86aec89ff44e0b1a82ebed9a7451b	CC BY 4.0
Top Hat	Borgen	https://sketchfab.com/3d-models/top-hat-689cd0d635cf4906920dd3ba435d991e	CC BY 4.0
Top hat	Filip	https://sketchfab.com/3d-models/top-hat-acc9845b7c48479c9b23d93d3643612f	CC BY 4.0
Water Gun	Tomas Peralta	https://sketchfab.com/3d-models/water-gun-3fd818df2fa740dea108ca3b8bb1a5d0	CC BY 4.0
Watergun VR Ready	adarose	https://sketchfab.com/3d-models/watergun-vr-ready-f58fab90aa204d168d9c36208ce7ce62	CC BY 4.0
Watering Can	Studio Lab	https://sketchfab.com/3d-models/watering-can-d294b334b9ab44f2914b80b20aaf188c	Standard
Watering can 2	Virtual Museums of Małopolska	https://sketchfab.com/3d-models/watering-can-2-3ef6b5739d4f4aff8bdafe7498150d04	CC0 1.0
Nintendo Wii (RVL-001)	Djsigksj	https://sketchfab.com/3d-models/nintendo-wii-rvl-001-84d7958819f34ab6ad4d30dbbaed11c3	CC BY 4.0
WII Console	Twisty_z	https://sketchfab.com/3d-models/wii-console-b13a4c0289144aa9b436d8de72e6a7a0	CC BY 4.0

Note. Standard refers to Sketchfab Standard License.

Appendix C Full Statistical Model Outputs for Study 1

Table 11 Study 1 Free Recall

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	-1.55	0.07	-21.52	< .001	-
Motion E	-0.05	0.06	-0.92	.359	-
Motion R	-0.04	0.10	-0.43	.668	-
E-R context	0.16	0.05	3.39	< .001	Same: 0.22 (0.11) Different: 0.20 (0.12)
Schema-Relevance	0.03	0.05	0.49	.624	Relevant: 0.22 (0.13) Irrelevant: 0.21 (0.11)
E-R context * Schema-Relevance	0.21	0.09	2.27	.023	Same Context, Relevant Schema: 0.24 (0.16) Same Context, Irrelevant Schema: 0.21 (0.12) Different Context, Relevant Schema: 0.20 (0.17) Different Context, Irrelevant Schema: 0.20 (0.13)

Note. Motion E and *Motion R* variables controlled for whether background components for the given trial were dynamic or static. *E-R context* refers to whether the encoding/retrieval contexts were the same or different.

Table 12 Study 1 Hit Rate

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	1.87	0.08	-22.83	< .001	-
M E	-0.03	0.06	-0.53	.599	-
M R	-0.17	0.12	-1.47	.141	-
E-R context	0.09	0.05	1.82	.069	Same: 0.84 (0.10) Different: 0.83 (0.12)
Schema-Relevance	-0.08	0.06	-1.39	.165	Relevant: 0.82 (0.13) Irrelevant: 0.84 (0.10)
E-R context * Schema-Relevance	-0.16	0.10	-1.62	.106	Same Context, Relevant Schema: 0.82 (0.15) Same Context, Irrelevant Schema: 0.85 (0.11) Different Context, Relevant Schema: 0.81 (0.15) Different Context, Irrelevant Schema: 0.83 (0.13)

Table 13 Study 1 Lure Discrimination

	β	SE	Z	p	*M (SD)*
Intercept	1.36	0.09	15.47	< .001	-
M E	-0.12	0.06	-2.00	.045	-
M R	0.00	0.12	0.00	.997	-
E-R context	-0.05	0.05	-1.12	.261	Same: 0.75 (0.13) Different: 0.75 (0.13)
Schema-Relevance	-0.08	0.05	-1.65	.099	Relevant: 0.72 (0.14) Irrelevant: 0.77 (0.12)
E-R context * Schema-Relevance	-0.08	0.09	-0.90	.370	Same Context, Relevant Schema: 0.72 (0.17) Same Context, Irrelevant Schema: 0.76 (0.14) Different Context, Relevant Schema: 0.73 (0.18) Different Context, Irrelevant Schema: 0.77 (0.14)

Table 14 Study 1 False Alarm Rate

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	-2.88	0.13	-22.98	< .001	-
M E	0.09	0.08	1.12	.263	-
M R	-0.07	0.14	-0.54	.592	-
E-R context	0.17	0.06	2.67	.008	Same: 0.12 (0.08) Different: 0.11 (0.08)
Schema-Relevance	0.02	0.07	0.22	.829	Relevant: 0.12 (0.10) Irrelevant: 0.12 (0.08)
E-R context * Schema-Relevance	0.10	0.12	0.80	.426	Same Context, Relevant Schema: 0.13 (0.13) Same Context, Irrelevant Schema: 0.12 (0.09) Different Context, Relevant Schema: 0.11 (0.12) Different Context, Irrelevant Schema: 0.11 (0.10)

Appendix D Full Statistical Model Outputs for Study 2

Table 15 Study 2 Free Recall

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	-1.34	0.10	-12.85	< .001	-
E-R context	0.16	0.09	1.84	.066	Same: 0.25 (0.13) Different: 0.23 (0.14)
Schema-Relevance	0.05	0.10	0.53	.597	Relevant: 0.26 (0.14) Irrelevant: 0.23 (0.12)
E-R context * Schema-Relevance	-0.05	0.18	-0.30	.766	Same Context, Relevant Schema: 0.28 (0.15) Same Context, Irrelevant Schema: 0.24 (0.15) Different Context, Relevant Schema: 0.24 (0.18) Different Context, Irrelevant Schema: 0.22 (0.15)

Table 16 Study 2 Hit Rate

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	1.88	0.12	15.24	< .001	-
E-R context	0.14	0.10	1.40	.160	Same: 0.83 (0.13) Different: 0.82 (0.13)
Schema-Relevance	-0.14	0.11	-1.31	.189	Relevant: 0.80 (0.14) Irrelevant: 0.84 (0.12)
Object Grasp	-0.11	0.10	-1.13	.259	Grasp: 0.82 (0.13) Point: 0.83 (0.13)
E-R context * Schema-Relevance	0.31	0.20	1.54	.123	Same Context, Relevant Schema: 0.82 (0.16) Same Context, Irrelevant Schema: 0.84 (0.14) Different Context, Relevant Schema: 0.78 (0.18) Different Context, Irrelevant Schema: 0.84 (0.13)
E-R context * Object Grasp	-0.02	0.20	-0.10	.923	Same Context, Grasp: 0.83 (0.14) Same Context, Point: 0.84 (0.15) Different Context, Grasp: 0.82 (0.15) Different Context, Point: 0.82 (0.15)
Schema-Relevance * Object Grasp	-0.17	0.20	-0.85	.396	Relevant Schema, Grasp: 0.79 (0.16) Relevant Schema, Point: 0.82 (0.16) Irrelevant Schema, Grasp: 0.84 (0.13) Irrelevant Schema, Point: 0.84 (0.13)
E-R context * Schema-Relevance * Object Grasp	-0.12	0.40	-0.31	.756	Same Context, Relevant Schema, Grasp: 0.81 (0.18) Same Context, Relevant Schema, Point: 0.84 (0.20) Same Context, Irrelevant Schema, Grasp: 0.83 (0.15) Same Context, Irrelevant Schema, Point: 0.84 (0.16) Different Context, Relevant Schema, Grasp: 0.77 (0.21) Different Context, Relevant Schema, Point: 0.79 (0.21) Different Context, Irrelevant Schema, Grasp: 0.84 (0.15) Different Context, Irrelevant Schema, Point: 0.84 (0.15)

Table 17 Study 2 Lure Discrimination

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	1.37	0.10	13.13	< .001	-
E-R context	0.00	0.09	0.04	.965	Same: 0.75 (0.11) Different: 0.75 (0.11)
Schema-Relevance	-0.08	0.10	-0.83	.406	Relevant: 0.74 (0.14) Irrelevant: 0.76 (0.10)
Object Grasp	0.10	0.09	1.07	.283	Grasp: 0.76 (0.11) Point: 0.75 (0.12)
E-R context * Schema-Relevance	0.17	0.18	0.95	.342	Same Context, Relevant Schema: 0.75 (0.17) Same Context, Irrelevant Schema: 0.75 (0.13) Different Context, Relevant Schema: 0.73 (0.16) Different Context, Irrelevant Schema: 0.77 (0.12)
E-R context * Object Grasp	0.19	0.18	1.04	.298	Same Context, Grasp: 0.76 (0.13) Same Context, Point: 0.74 (0.16) Different Context, Grasp: 0.75 (0.15) Different Context, Point: 0.75 (0.12)
Schema-Relevance * Object Grasp	0.02	0.18	0.10	.922	Relevant Schema, Grasp: 0.75 (0.18) Relevant Schema, Point: 0.73 (0.15) Irrelevant Schema, Grasp: 0.76 (0.13) Irrelevant Schema, Point: 0.76 (0.13)
E-R context * Schema-Relevance * Object Grasp	0.41	0.36	1.13	.257	Same Context, Relevant Schema, Grasp: 0.78 (0.20) Same Context, Relevant Schema, Point: 0.72 (0.22) Same Context, Irrelevant Schema, Grasp: 0.75 (0.16) Same Context, Irrelevant Schema, Point: 0.75 (0.17) Different Context, Relevant Schema, Grasp: 0.72 (0.23) Different Context, Relevant Schema, Point: 0.74 (0.17) Different Context, Irrelevant Schema, Grasp: 0.77 (0.18) Different Context, Irrelevant Schema, Point: 0.76 (0.15)

Table 18 Study 2 False Alarm Rate

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	-2.60	0.15	-17.52	< .001	-
E-R context	0.13	0.12	1.07	.285	Same: 0.14 (0.08) Different: 0.13 (0.07)
Schema-Relevance	-0.03	0.14	-0.19	.847	Relevant: 0.13 (0.09) Irrelevant: 0.14 (0.07)
Object Grasp	-0.20	0.12	-1.61	.108	Grasp: 0.13 (0.07) Point: 0.14 (0.07)
E-R context * Schema-Relevance	-0.11	0.25	-0.47	.641	Same Context, Relevant Schema: 0.13 (0.13) Same Context, Irrelevant Schema: 0.15 (0.09) Different Context, Relevant Schema: 0.14 (0.10) Different Context, Irrelevant Schema: 0.13 (0.09)
E-R context * Object Grasp	-0.24	0.25	-0.98	.328	Same Context, Grasp: 0.13 (0.10) Same Context, Point: 0.15 (0.11) Different Context, Grasp: 0.13 (0.09) Different Context, Point: 0.14 (0.09)
Schema-Relevance * Object Grasp	-0.02	0.25	-0.08	.935	Relevant Schema, Grasp: 0.12 (0.12) Relevant Schema, Point: 0.14 (0.11) Irrelevant Schema, Grasp: 0.13 (0.08) Irrelevant Schema, Point: 0.14 (0.09)
E-R context * Schema-Relevance * Object Grasp	-0.64	0.49	-1.29	.196	Same Context, Relevant Schema, Grasp: 0.10 (0.15) Same Context, Relevant Schema, Point: 0.15 (0.18) Same Context, Irrelevant Schema, Grasp: 0.15 (0.11) Same Context, Irrelevant Schema, Point: 0.15 (0.12) Different Context, Relevant Schema, Grasp: 0.14 (0.15) Different Context, Relevant Schema, Point: 0.13 (0.13) Different Context, Irrelevant Schema, Grasp: 0.12 (0.11) Different Context, Irrelevant Schema, Point: 0.14 (0.12)

Appendix E Full Statistical Model Outputs for Study 3

Table 19 Study 3 Free Recall

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	-1.74	0.14	-12.31	< .001	-
M E	-0.09	0.19	-0.48	.632	-
M R	0.01	0.22	0.03	.979	-
E-R context	0.10	0.14	0.71	.479	Same: 0.17 (0.10) Different: 0.17 (0.09)
Schema-Relevance	0.42	0.15	2.89	.004	Relevant: 0.21 (0.11) Irrelevant: 0.15 (0.07)
E-R context * Schema-Relevance	0.68	0.28	2.40	.016	Same Context, Relevant Schema: 0.24 (0.19) Same Context, Irrelevant Schema: 0.14 (0.09) Different Context, Relevant Schema: 0.18 (0.12) Different Context, Irrelevant Schema: 0.17 (0.11)

Table 20 Study 3 Hit Rate

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	1.87	0.21	8.95	< .001	-
M E	-0.50	0.20	-2.52	.012	-
M R	0.32	0.38	0.85	.394	-
E-R context	-0.16	0.14	-1.19	.233	Same: 0.82 (0.13) Different: 0.84 (0.12)
Schema-Relevance	-0.12	0.14	-0.85	.396	Relevant: 0.82 (0.15) Irrelevant: 0.84 (0.12)
E-R context * Schema-Relevance	0.03	0.27	0.09	.925	Same Context, Relevant Schema: 0.81 (0.17) Same Context, Irrelevant Schema: 0.83 (0.13) Different Context, Relevant Schema: 0.83 (0.16) Different Context, Irrelevant Schema: 0.85 (0.13)

Table 21 Study 3 Lure Discrimination

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	1.35	0.19	7.24	< .001	-
M E	-0.02	0.19	-0.09	.930	-
M R	0.46	0.33	1.43	.154	-
E-R context	0.12	0.12	1.02	.308	Same: 0.74 (0.13) Different: 0.71 (0.17)
Schema-Relevance	0.15	0.13	1.11	.269	Relevant: 0.73 (0.15) Irrelevant: 0.72 (0.14)
E-R context * Schema-Relevance	-0.10	0.25	-0.41	.682	Same Context, Relevant Schema: 0.73 (0.17) Same Context, Irrelevant Schema: 0.74 (0.15) Different Context, Relevant Schema: 0.72 (0.21) Different Context, Irrelevant Schema: 0.71 (0.18)

Table 22 Study 3 False Alarm Rate

	β	*SE*	*Z*	*p*	*M (SD)*
Intercept	-2.60	0.21	-12.70	< .001	-
M E	0.02	0.24	0.08	.937	-
M R	-0.09	0.28	-0.33	.743	-
E-R context	-0.11	0.17	-0.63	.530	Same: 0.12 (0.07) Different: 0.13 (0.08)
Schema-Relevance	-0.22	0.18	-1.17	.244	Relevant: 0.12 (0.07) Irrelevant: 0.13 (0.08)
E-R context * Schema-Relevance	0.05	0.34	0.14	.890	Same Context, Relevant Schema: 0.12 (0.11) Same Context, Irrelevant Schema: 0.13 (0.08) Different Context, Relevant Schema: 0.12 (0.10) Different Context, Irrelevant Schema: 0.14 (0.10)

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