Event Segmentation and Memory: Optimising Episodic Encoding within a Virtual Environment.

Matthew R. Logie

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Declaration

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Abstract

This thesis describes ten experiments exploring the role event boundaries play in the transfer of information from short- to long-term memory. In doing so the thesis explores the interaction between working memory and episodic memory, asking whether it is possible to optimise encoding using experimentally imposed event segmentation. The studies were inspired by the Method of Loci, where participants are trained to use visuo-spatial imagery as a strategy to enhance memory. Here, however, we employed an innovative self-made event-sequencing virtual environment that allows the boundaries between to-be-remembered words to be imposed and manipulated during learning. Previous work suggests that the presence of doorways may signal an event boundary, providing structure that enhances memory transfer. An initial set of experiments identified a memory improvement effect when word lists were segmented via the presence of doorways, but similar improvements were found when segmentation was achieved solely via gaps in space or time. A second set of experiments explored the possibility that memory can be optimised by manipulating the quantity and domain of information presented between event boundaries. Findings revealed that both overloading (by presenting highly imageable words between boundaries) and underloading (by limiting visual-spatial information between boundaries) working memory had a detrimental impact on memory. Taken together the results suggest there is a time- and item-limited 'Goldilocks zone' that optimally supports the transfer of information into long-term memory. More broadly, the data confirms that working memory is a distinct system, and the pattern of boundaries experienced between events directly affects the likelihood of successfully transferring information into long-term memory. Findings are discussed in relation to current theories of working memory and event segmentation, highlighting that long-term learning involves the simulation of events within working memory, and demonstrating that virtual learning environments can be used to create event boundaries and enhance memory.

Contents

Chapter 1

Introduction

Memory is a fundamental part of the human cognitive system, supporting a wide range of everyday behaviours. Because it is so essential for normal functioning, the study of memory has become a topic of great interest in psychological research and many different approaches have been used to gain understanding of how memory operates (from molecular to systems level). Traditional studies of memory have often focused on understanding how the processes and systems are constrained by capacity limitations or experimental manipulations, or how they are affected by memory decline in aging or disease states. In contrast, the approach taken here is to examine under what conditions human memory can operate at peak performance and to systematically deconstruct and isolate the components that might contribute to superior memory performance. I begin, therefore, by considering an early insight into how memory can be enhanced that was made by the Ancient Greeks, known as the Method of Loci. As I outline below, the Method of Loci is used as a reference point for the examination of current theoretical accounts of memory, with the aim of identifying the components that may contribute to peak memory performance.

The starting question for the present research is to ask, 'What processes of memory are responsible for the effectiveness of the Method of Loci?'. The following review will therefore first define and discuss the Method of Loci. The review will then focus on one account of memory formation, known as Event Segmentation Theory, which proposes a fundamental organisation of memory involving the segmentation of a continuous flow of information to provide sequences of events. The review will then provide an overview of current theories of Working Memory and Episodic Memory, before discussing the use of Event Segmentation Theory to provide a theoretical account of the interactions between working and episodic memory. As well as discussing current theories of memory, the introduction outlines the benefits of using virtual environments to examine memory (e.g., providing control over the presentation of stimuli), highlighting the methods that will be used within this thesis. Finally, I outline the statistical approach adopted in the work presented here, providing an argument for the benefits of comparative (Bayesian) statistics over the use of frequentist (p-value) statistics.

Put simply, the research reported here makes use of a custom-built virtual environment to examine the components that define an individual memory. Critically, I take an explicitly reductionist approach, first attempting to find a memory improvement effect and then systematically removing components of the experiment to make the effect disappear (thereby providing evidence that the removed component was important for causing the effect). Using this approach, I first seek to identify whether a memory improvement effect can be found. To what extent will memory performance differ when presenting to-be-learned content in either unsegmented or segmented conditions across a series of virtual rooms? After finding a memory improvement effect I then seek to identify the importance of prediction errors and the components that are required for defining the boundaries between events, such as changes of context, the presence of spatial-temporal gaps or the presence of walls and doorways. Having established the components that are important for defining the boundaries between events, I subsequently aimed to identify the potential limits for an optimal amount of information that is present between boundaries. In particular, the thesis tests the prediction that there may be a “Goldilocks zone” that best supports episodic encoding, when the amount of information between boundaries can be maintained within working memory. The primary aim of the research is to isolate and define the components that are required to optimise episodic encoding and to use that knowledge to develop theoretical understanding of the formation of episodic memories. The segmentation of information (based on the presence of event boundaries) has been proposed as a core function for working memory updating and is considered essential to the successful encoding and retrieval of information from episodic memory. In essence, therefore, the present thesis asks two key questions, “What are the components that are crucial for the segmentation of to-be-remembered information?” and “Can the presence of event boundaries be manipulated to optimise episodic encoding?”

1.1 Mnemonics and the Method of Loci

The journey begins in ancient Greece, at a wealthy nobleman’s banquet, where Simonides of Ceos is said to have recited a poem to the assembled guests. Upon finishing his recital Simonides left the hall and a few moments later the roof of the hall collapsed, killing the attending guests. In the aftermath of the event Simonides realised that he could recall the names, faces and locations of everyone that was present. Simonides was recalling a real event; however, making use of imagined images and locations also works when placing to-be remembered information in fictional locations. The story of Simonides began the development of the Method of Loci (Yates, 1966), also known as the memory palace technique (Spence, 1985). The Method of Loci remains one of the best known and most widely used mnemonic techniques that an individual can employ to greatly increase the amount of information they can remember.

The most extensive version of the Method of Loci involves time-consuming training in the ability to form a detailed mental image of a spatial environment, one that the mnemonist can imagine travelling through, or can mentally view as a spatial layout (Qureshi, Rizvi, Syed, Shahid & Manzoor, 2014; Butcher, 2000). Images, alongside their labels, can be placed at distinct locations within the environment and the mnemonist can then recall the to-be-remembered information that they place within this memory palace by re-imagining the specific area in which it was stored. The same environment could be used for multiple lists, as the extremely detailed navigational knowledge of the spatial layout allows each area to be expanded and isolated. A simpler less training intensive version of the Method of Loci involves imagining the items on a list as objects and placing them in locations around a simple familiar environment. The benefit of this mnemonic technique is well illustrated by the following quote from the Art of Memory, "There are two kinds of memory, he continues, one natural, the other artificial. The natural memory is that which is engrafted in our minds, born simultaneously with thought. The artificial memory is a memory strengthened or confirmed by training. A good natural memory can be improved by this discipline and persons less well-endowed can have their weak memories improved by the art." (Yates, 1966, p. 20).

One interpretation of the Method of Loci suggests the memory benefits result from the creation of connections between words, images and locations. In other words, using imagination to generate visuo-spatial imagery or to construct discrete scenes of the to-be-remembered information. Importantly, empirical studies have shown that the Method of Loci does provide substantial memory improvements over the use of simple imagery or repetition, as well as providing improvements over semantically linking words to each other within the same list. In addition, the same environment can be used many times for different information without the build-up of interference (Roediger, 1980; De Beni & Cornoldi, 1985; Wang & Thomas, 2000). In the Art of Memory, Yates (1966) provides detailed descriptions of how best to train the mind for memory, including recommendations that a) the locations should be distinct, b) there should not be too many 'intercolumnar spaces' (the gaps between supporting columns of a building), and c) there should be a definite marker after every fifth item. If the student in the art of memory does not have access to enough real space, then the locations can be imagined, fictional spaces (Yates, 1966).

As noted above, from the mnemonist's perspective the Method of Loci simply involves creating associations between words, images and locations. Nonetheless, the training has measurable physiological consequences. For example, training elderly participants in this method has been shown to result in a thickening of cortical structures (Envig *et al*., 2010) and to provide short-term improvements to the integrity of white matter (Envig *et al*., 2012). The method is also sufficiently effective to have become widely used by memory athletes, who compete to see how much they can remember within a certain amount of time. For example, the Method of Loci has provided the basis for one of the current records in memorising 130 random words within 5 minutes (Foer, 2011; World-memory-statistics, 2018). Importantly, evidence also suggests that the abilities of memory athletes are the result of training, rather than being due to any innate ability (Maguire *et al.,* 2003; Dresler & Konrad, 2013). For example, Dresler *et al*., (2017) compared memory athletes to a control group matched for age, sex, intelligence and handedness. After 6 months of training in the Method of Loci the control group could remember up to 36 more words than previously.

The traditional Method of Loci approach has been assumed to require a highly detailed memory of a familiar environment and clear definitive images of the objects to be remembered (Moe & De Beni, 2005). Differences in memory performance may be found for words with high imageability or concreteness and words with low imageability or concreteness (Allen & Hulme, 2006; Paivio, 1971; Walker & Hulme, 1999). However, recent evidence suggests that the Method of Loci may provide an improvement to the number of words remembered regardless of the image-ability or concreteness of the words and that the mnemonist need not necessarily employ either a real or imagined environment. For example, Legge, Madan, Ng & Caplan (2012) created virtual environments using game development software and found that a recently encountered virtual environment was just as effective as the traditional Method of Loci and memory benefits were not unique to high-imageability words. In addition, and contrary to expectation, these virtual environments did not need to be richly detailed or highly familiar for memory improvements to occur. Contrary to the traditional method, when a virtual environment was employed very little training was required to make use of the Method of Loci.

One important feature of the Method of Loci is that to-be-remembered information is separated into discrete locations, suggesting that segmenting any kind of information may result in enhanced memory performance. Empirical evidence strongly supports this view. For example, Qureshi, Rizvi, Syed, Sahid & Manzoor (2014) conducted a study of medical students to see if the Method of Loci could be used to improve learning. One group of participants were given didactic-lectures and self-directed learning sessions, while the other group were given didactic lectures and Method of Loci training. The group that received Method of Loci training showed substantially greater improvements in the subsequent assessments than the self-directed learning group. Similarly, in a study of mnemonic training, Roediger (1980) compared the effectiveness of several mnemonic techniques. Participants were split into several groups; every group completed an initial test where they were asked to recall as many words as possible from a presented list. One group was asked to conduct additional rehearsals after every fourth word that was presented, a second group was asked to imagine each word, and a third group was asked to link each word with an image of the word that was presented immediately before it. Group four received training in the peg-word mnemonic in which presented words were associated with 'pegs' placed in the lines of a memorised rhyme (one is a gun, two is a shoe, three is a tree, etc). Finally, group five received training in the Method of Loci, where the words were associated with familiar locations. The linking mnemonic, the peg-word mnemonic and the Method of Loci all resulted in an increase in words recalled and an increase in recalling the words in the order of presentation (in comparison with simply imagining images or conducting additional rehearsals). In addition, the peg-word mnemonic and the Method of Loci groups showed the largest increase in both the number of words recalled and in recalling the words in the order of presentation. Learning to segment to-be-remembered words with a sequence of definite markers, such as the locations around a home or the lines of a rhyme resulted in an enhanced memory performance.

While the Method of Loci was originally believed to require distinct familiar locations, a further study of mnemonic training sought to identify whether purely temporal or procedural markers could provide similar memory benefits. Bouffard *et al.*, (2017) compared i) training in the Method of Loci, where each participant used locations from their own home, to ii) training with an autobiographical mental timeline, and iii) training in the use of procedural markers, represented by the steps to making a sandwich. All three methods resulted in an increase in the number of words recalled in delayed free recall relative to uninstructed free recall. In addition, all three methods resulted in an increase in recalling the words in the order of presentation. The results also showed, however, that participants learned to use the Method of Loci more quickly than either the autobiographical timeline or sandwich making steps, suggesting that there is an additional benefit to the use of spatial gaps between to-be-remembered items. An important implication of this finding (and one that I return to later in the thesis) is that when the Method of Loci involves segmenting information with spatial and temporal gaps, the benefits to memory should be greater than when segmentation is achieved using temporal gaps alone. The study also demonstrated that memory performance only improved if the participants employed a mnemonic strategy, confirming that the results were not simply due to having the opportunity to practice with remembering an initial word list prior to training.

As the foregoing discussion suggests, the traditional Method of Loci approach generally involves several time-consuming training sessions (Brehmer, Li, Muller, Von Oertzen & Lindeberger, 2007; Brooks, Friedman & Yesavage, 1993). However, as noted earlier, Legge *et al*. (2012) compared memory for words using the traditional Method of Loci with memory for words using locations that were recently encountered in a virtual environment. The comparison showed that less than 5 minutes of training within a virtual environment could provide benefits that are equivalent to those found with the traditional Method of Loci. The finding is, of course, consistent with the earlier description of the Method of Loci (Yates, 1966), which suggested that fictional spaces could be employed in place of real locations. Given that the nature of the locations themselves is not critical, these findings also raise the possibility that the effectiveness of the Method of Loci could be due to the fact it involves efficiently segmenting packets of information, such that the information can easily be maintained within working memory. Alternatively, rather than explicitly due to segmentation benefits may be described in terms of clustering of to-be remembered information in space and time, a concept to which I will return. Having explored the benefits of the Method of Loci mnemonic, and what features of the method might contribute to those benefits, I now turn to Event Segmentation Theory as a potential explanatory framework that can account for the effectiveness of this, and similar mnemonic techniques.

2. Event segmentation

Event Segmentation Theory (EST) provides a framework for how the continuous stream of information encountered throughout life is integrated into a sequence of events which provide a lasting episodic experience. Zacks & Tversky (2001, p. 2) defined an event as "a segment of time at a given location that is perceived by an observer to have a beginning and an end." From this perspective, events can be thought of as the fundamental units of episodic memory. Event Segmentation Theory also proposes the construction of mental models: events are held in working memory to provide a representation of the present moment, allowing predictions to be made about the near future. According to EST, encountering a mismatch to the prediction (i.e., a prediction error) is experienced as a boundary that causes the mental model to update. Moreover, perceiving segmented temporal sequences of events is considered crucial for understanding laws of cause and effect, as well as for forming discrete memories from the ongoing experiences of life.

2.1 Origins

Before detailing modern studies of EST, I will first provide a review of the theory's origins. EST grew out of the ideas expressed within Gestalt psychology (Kohler, 1929), particularly the idea that the whole is greater than the sum of its parts. The Gestalt laws of perceptual organisation demonstrated that perceived items are grouped by laws such as similarity, proximity or sharing a common region. For the law of common region, items displayed within a space encircled by a boundary line are perceived as a group, even though the items close to the boundary line may be spatially closer to items outside of the boundary line. The law of common region describes how the items encountered within a room are grouped together, even though items on either side of a doorway may be spatially and temporally closer together, an idea to which I will return later.

Building on the Gestalt laws, Biederman (1987) proposed a Recognition by Components theory. Biederman designed a series of experiments which systematically removed parts of an image of an object represented in line drawings. Identifying the presented images was found to be harder if the corners of the image were removed than when the lines between the corners where removed. While the results were interpreted in terms of ‘Geons’ (fundamental units of visual information akin to the fundamental phonemes of language) the results could also be interpreted in terms of boundary retention. According to this view, retaining the boundaries of a presented object provides enough information for the object to be identified. The Gestalt laws and the studies of Biederman demonstrate powerful grouping mechanisms present for visual information. In essence, Event Segmentation Theory accounts for the fact that similar principles can be found in studies of segmentation in memory.

2.2 Films

The original experiments that led to Event Segmentation Theory were based on a pioneering paradigm that employed film clips (Newtson, 1973; Newtson & Enquist, 1976). The experiments aimed to explore how a participant might parse a continuous stream of information into discrete parts. The paradigm involved showing a group of participants film clips and asking them to press a button when, in their view, a meaningful moment came to an end. The marked moments were used to identify breakpoints in the films and subsequent film clips were created with deleted sections. The deleted sections were either at non-breakpoints or breakpoints. Participants in subsequent experiments exhibited poorer memory for the actions within the film (and the order of events) for the film clips containing breakpoint deletions, than for film clips containing non-breakpoint deletions. Further studies made use of the film clip paradigm and demonstrated improved recognition and recall for information encountered close to a boundary breakpoint (Schwan *et al*., 2000). In an extension of this early work, more recent studies have shown that inserting additional pauses between film scenes results in improved memory performance for the events, whereas inserting pauses in the middle of a film scene impairs performance (Boltz, 1992; Schwan *et al*., 2000).

To some extent it is perhaps unsurprising that the structure and sequence of events within films is important. After all, the role of a film director is to construct memorable sequences of events, in effect to provide segmented narratives, so that audiences can remember and find meaning within the film. Further studies of segmentation in film examined the experience of passing through space and time (Magliano, Miller & Zwaan, 2001). Shifts in space and time were initially identified within a film, before subsequent judgements of the shifts were made by participants. The participants whose judgements more closely matched the predefined shifts exhibited improved memory performance in comparison to participants whose judgements did not closely match the shifts. It is important to acknowledge, however, that films are not entirely equivalent to the kinds of stimuli learned in memory experiments. For example, the narrative events of films are causally connected and occur within a specific location, at a discrete moment in time, and film directors know that the ability to identify the changes in space and time and the connections between events are important processes for the memorability of narrative events. Nonetheless, just as the boundaries of visual images are important for recognising objects, event boundaries in films play an important role in subsequent memory performance.

The segmentation of films has proved to be a powerful tool for examining memory performance and studies of event memory have demonstrated that there is a strong relationship between the segmentation of events and subsequent memory performance (Ezzyat & Davachi, 2011; Schwan, Garsoffky & Hesse, 2000). For example, associations between to-be-remembered items are stronger within an event than between events, consistent with the grouping mechanisms of perceptual organisation. Furthermore, individual differences in segmentation ability can predict subsequent memory performance (Bailey *et al*., 2013; Kurby & Zacks, 2011). For example, Bailey and colleagues employed the button pressing paradigm described above, finding that individuals whose segmentation ability lined up with the majority of the group showed an improved memory performance in comparison to individuals whose segmentation did not line up with the majority of the group. Evidence suggests, however, that a participant's ability to efficiently segment films predicts memory performance above and beyond other measures of memory. Support for this view comes from Sargent *et al*. (2013) who tested event memory in adults between the ages of 20 and 79. Participants were asked to press buttons to segment films, before performing tests of memory for the contents of the film. Participants were also given psychometric tests, including measures of working memory capacity and perceptual processing speed. Segmentation ability was defined as the extent to which the boundaries identified by a participant aligned with the majority of the group of participants. Again, memory performance was found to be greatest for the participants whose segmentation lined up with the majority of the group. Importantly, the results also revealed that segmentation ability uniquely predicts memory performance independently from psychometric tests of other cognitive abilities. Taken together, therefore, these data suggest that segmenting scenes into events is a fundamental process that influences memory performance in everyday life.

Whilst the evidence reviewed above demonstrates the immediate impact of segmentation on memory performance, wider evidence suggests that there are also long-lasting consequences. In particular, researchers have demonstrated that efficiently segmenting films provides memory improvements that are still present a month later. Flores, Bailey, Eisenberg & Zacks (2017) conducted a study to examine event memory at multiple time delays after participants engaged with the button pressing paradigm to segment films. Individual differences in segmentation predicted memory performance when participants were tested a month later. While participants have a natural segmentation ability that influences memory performance, the authors proposed that providing training to efficiently segment information could provide a means of training memory to aid learning (e.g., for patients with clinical conditions associated with memory impairments).

Further differences in memory performance can be found by asking participants to segment a presented film and separating participants into groups of over-segmenters and under-segmenters (Jafarpour *et al*., 2019). Participants who over segment exhibit improved memory for the contents of the film, whereas participants who under segment demonstrate an improved memory for temporal order. More importantly, perhaps, the differences in over- and under-segmenting suggests that it should be possible to optimise memory performance by manipulating the number of boundaries and the amount of information between boundaries. In support of this view, studies involving the segmentation of films have demonstrated that participants who efficiently segment events will show an improved memory performance in comparison to participants who do not efficiently segment events (Zacks, Speer, Swallow & Maley, 2010).

2.3 Language

Another line of research that contributed to the development of Event Segmentation Theory is that of ‘situation models’ in studies of language comprehension. Several influential studies introduced theories of situation models (Bransford, Barclay & Franks, 1972; Glenberg, Meyer & Lindem, 1987; Zwaan & Radvansky, 1998) and demonstrated that seemingly subtle changes in the language used to describe a situation can have a powerful effect on subsequent memory performance. According to this view language comprehension is dependent on constructing a situation model, such as imagining a representation of what the language is describing. The Event-Indexing Model was an initial attempt to specifically describe the representation of situation models (cf. Zwaan, Langston & Graesser, 1995; Zwaan, Magliano & Graesser, 1995; Zwaan & Radvansky, 1998). A situation model is composed of sequences of events maintained within working memory, with each event related to all other events in dimensions such as space, time, entity, causation and motivation. According to this view, successive events can overlap on any combination of dimensions to form situation models. The more dimensions involved and the more overlap there is for successive events maintained within working memory, the easier it will be to comprehend the events and the more robust the long term-memory for the sequences of events will be. New situation models are created when the dimensions change, such as describing a new location, at a later time, with different characters. In the study by Bransford *et al*. (1972) participants listened to similar sentences with seemingly subtle changes to the language:

Three turtles rested *on* a floating log, and fish swam beneath *them.*
Three turtles rested *on* a floating log, and fish swam beneath *it.*

Three turtles rested *beside* a floating log, and fish swam beneath *them.*
Three turtles rested *beside* a floating log, and fish swam beneath *it.*

When subsequently tested for comprehension, results revealed that participants were more likely to confuse the first and second sentences than the third and fourth sentences (because participants are grouping the turtles and the log in the first instance, whereas the turtles and the log are in separate groups in the second instance). These findings have been interpreted as support for the view that language comprehension is dependent on constructing a situation model, such as imagining grouped representations of the scene the language is describing. Why are situation models necessary? Put simply, psycholinguists argue that being able to combine information from sequences of sentences, and therefore being able to follow a story, requires grouping of information from multiple sentences – each of which would hold too much information to be comfortably held within working memory. From this perspective, therefore, sentences form the basic units (i.e., sub-parts) of events and the situation model is required to explain how the units fit together.

While situation models have been proposed as being dependent on at least five dimensions, for the present thesis the dimensions of time and space are of most interest. Studies of reading have shown that when sentences describe a change of location, or a passing of time, readers slow down their reading pace (Zwaan, 1995). Further studies have shown a slowing of reading time in narrative text (Speer & Zacks, 2005). For example, the inclusion of the phrase ‘an hour later’ in the narrative caused participants to read more slowly, consistent with the idea that the phrase identified an event boundary which marked the end of the current event and prepared participants for the next event. A further study that directly tested memory for sentences gave participants narratives that contained event boundaries (Ezzyat & Davachi, 2011). During a subsequent test phase, participants were given a sentence and asked which sentence came next. The next sentence was more easily recalled when there was no event boundary between the two sentences, suggesting that participants were more likely to cluster information from the same event and that boundary phrases marked the ends of events.

Taken together, the findings from studies of language comprehension clearly demonstrate that recalling what came next is easier if what came next was part of the same event. While there are benefits to recalling information from within the same event, providing boundaries can also improve memory for words encountered after the boundary. For example, Corley *et al*. (2007) conducted a study of memory for words in sentences that made use of disfluencies within language. Sentence were presented aurally and some of the sentences included a hesitation by using the word ‘er’. The words encountered after the hesitation were more likely to be remembered. The memory benefits driven by the hesitations were also found after a delay of up to 55 minutes. That is, the presence of boundaries in the sentence structure provided benefits to memory at both short and long delays. Similar impacts on memory performance may be found when boundaries are provided by passing through doorways or moving between locations.

2.4 Location Updating Effect

As outlined above, studies of language comprehension show that the presence of hesitation and descriptions of spatial and temporal gaps within sentences has a powerful effect on subsequent memory performance for temporal order, as well as increasing the quantity of information available for recall. However, the effects of spatial and temporal gaps are also important for events that occur in the world during lived experiences. Imagine, for example, the following scene: a chef is in a busy restaurant kitchen and realises that they need an ingredient from the downstairs walk-in freezer. The chef exits the door of the kitchen, travels down the stairs into the freezer room and can no longer recall the required ingredient. Why, then, could the chef no longer recall the required ingredient? The explanation suggested by Event Segmentation Theory is that the event in the kitchen with the missing ingredient is held in working memory, however the event ceases to be maintained within working memory as soon as the chef carries out the actions they need to take to get to the freezer. According to this, view travelling through space and time, including activities such as passing through doorways, introduces contextual shifts that influence how information is segmented – which in turn influences memory.

Consistent with the foregoing chef scenario, Radvansky and Copeland (2006) explicitly claim that walking through doorways causes forgetting. This study involved a paradigm whereby participants picked up objects and carried them between rooms within a virtual environment, with segmentation being induced by the presence of doorways. Participants were tested for the names of the objects they were carrying, or the names of the objects they had recently dropped, either when still located within the same room or after travelling to the next room (introducing a spatial shift). Participants responded more quickly and accurately when tested for the object that they were currently carrying than when tested for the object that was dropped in the previous room. Moreover, lower levels of memory performance were found for items left behind in a previous room when compared with items carried without spatial shifts, replicating previous findings (Glenberg, Meyer & Lindem, 1987; Radvanksy & Copeland, 2001). The memory impairment was also present for both carried and dropped objects. That is, after a spatial shift memory performance was poorer for both the most recently dropped object and for the object that was currently being carried.

Further explorations of the 'walking through doorways' phenomenon sought to compare the effect of passing through doorways in both real and virtual environments (Radvansky, Krawietz & Tamplin, 2011). In addition, this follow up study sought to identify whether the effect could be explained in terms of encoding specificity – the idea that remembering information after returning to the same context as when the information is encoded improves performance (Thomson & Tulving, 1970). The memory impairment effect was found in both virtual environments using small displays and when travelling through doorways in a real environment. Furthermore, memory performance did not improve after participants picked up objects, passed through a doorway and subsequently returned to the same room. Critically. the result was not compatible with an encoding specificity account: passing through doorways impaired memory performance and returning to the same room, to reinstate the context, did not improve performance. The study also revealed that participants made a greater number of errors when multiple spatial shifts occurred, suggesting that it is the number of new events rather than the number of spatial shifts that is important. One potential interpretation of these findings is that the act of carrying objects between rooms causes the objects to be associated with multiple locations. According to this view the presence of multiple event models containing the same piece of to-be-remembered information produces an interference effect (Radvansky, 1999). The finding could also be explained in terms of a fan effect (Anderson & Reder, 1999), whereby associating the same item with multiple locations increases the difficulty of recall for any one event model (Radvansky, 1998; 1999; 2005; 2009).

The location updating effect was studied further by Radvanski *et al*. (2011) using virtual environments to provide the change in location. Research examining the location updating effect has demonstrated that large displays (i.e., that can fill a participant's visual field) provide more immersion and allow participants to experience a sense of being in the location that is represented (Bystrom, Barfield, & Hendrix, 1999). Given these findings, Radvansky *et al*. (2011) conducted an experiment that presented to-be-remembered information using screen size (17" or 66") to manipulate participants' level of immersion. The results of this experiment found that the location updating effect was still present even with the reduction in immersion, suggesting that virtual environments with low levels of immersion can provide the same sense of location produced by virtual environments with high levels of immersion. Also, virtual environments can provide a sense of location similar to that provided by real environments. As explained in more detail below, the experiments reported in the present thesis capitalise on the sense of location that virtual environments can provide.

An additional study of walking through doorways in virtual environments was conducted to determine if equivalent gaps in space and time would produce the memory impairment effect found when passing through doorways (Pettijohn & Radvansky, 2016). Participants were tasked with picking up objects in one room and either transporting them to another room, or simply moving the equivalent distance without passing through a doorway. Recognition memory was tested for objects that had either just been picked up, or just put down, with or without passing through a doorway. Memory performance was found to be impaired whenever participants passed through doorways. Importantly, however, when equivalent gaps in space and time occurred without passing through doorways the same memory impairment effect was not present. In a related experiment, Horner *et al*. (2016) also made use of a virtual environment, consisting of 48 connected rooms, each with different coloured wallpaper and separated by closed doors. Participants were asked to navigate through the virtual environment. Upon entering a room, participants were presented with an object on a table, which they were required to walk towards. After seeing the first object, it would disappear, and a second object would then appear on a second table. At test, participants were required to make old or new judgements about a series of presented objects. Regardless of their response, if the object was old, three additional old objects would be displayed, and participants were either asked which object came next, or which object came immediately before. Results revealed that participants were better at making correct judgements if the objects were within the same room. By contrast, if the participants had to pass through a door to get to the next object, it was more difficult to identify which object came next. The study also examined the effect of moving to a different context (i.e., as signalled by a change in wallpaper) *without* approaching a wall and passing through a doorway. In this case the change in context had no effect; there was no disruption of memory for which object came next. To be clear, the results showed that the disruption effect disappeared along with the spatial boundaries, suggesting that spatial boundaries provide structure to the way that a memory is formed, and the presence of doorways disrupts memory for temporal order.

In a further study of walking through doorways in a real environment, Pettijohn *et al*. (2016) explored the use of segmentation to improve long term memory performance. The study employed a variety of methods designed to encourage participants to segment word lists, including walking through doorways, switching between computer windows and the descriptions of ending and beginning events in narrative text. Across all methods, memory was found to improve when the word lists were segmented. This finding supports the view that segmentation is a general process that depends on boundary markers that can be defined in a variety of ways, including the dimensions of the Event-Indexing Model (as outlined above). Furthermore, the memory improvement effect was greater when employing two boundaries in comparison to one boundary. Again, taken together, the results suggest that memory performance may be further improved by increasing the number of boundaries and reducing the quantity of information between boundaries. Whilst the EST literature clearly suggests that segmentation can improve memory performance, it remains unclear which components are required to identify an event boundary that will provide an improved memory performance. Consequently, a primary aim of the current thesis is to identify which components are required to define boundaries that provide a memory improvement effect. An additional aim is to determine whether an optimal limit may be found for the number of boundaries and the quantity of information between boundaries. Are doorways or spatial temporal gaps crucial for driving improvements or reductions in memory performance?

Event Segmentation Theory proposes that event boundaries are commonly experienced at moments when changes are occurring (Zacks, 2020). The information encountered close to moments of change is remembered better than the information that occurs where little or no change occurs. Regardless of how an event is experienced, there are fundamental underlying processes governing the segmentation of information that influence the formation of discrete memories (Copeland, Magliano & Radvansky, 2006). Passing through doorways can be experienced as a significant change in the current situation, requiring participants to update their current situation model. From this perspective the influence of passing through doorways on memory performance can be interpreted in terms of the same situation models established in language studies and studies of film segmentation (Curiel & Radvanksy, 2002; Magliano, Miller & Zwaan, 2001; Zwaan *et al.*, 1998). More broadly, the impairments found when passing through doorways has been dubbed ‘the location updating effect’ (Radvansky & Copeland, 2006). The location updating effect is defined as an increased need for processing of updating information when passing through boundaries. Information encountered prior to a boundary is less available when tested after passing through the boundary. An interpretation of the memory impairment associated with passing through doorways is that event segmentation occurs upon encountering a boundary. Encountering a boundary such as walking through a doorway requires a new event model to be constructed and causes an updating of working memory (Kurby & Zacks, 2008; Swallow, Zacks & Abrams, 2009; Zacks, 2020). Furthermore, the current event is maintained within working memory, meaning that information for the current event can be more easily recalled (Glenberg *et al*., 1987). I will now examine further exploration of segmentation that may be driven without the need for spatial shifts.

2.5 Context-shifts

As outlined above, studies of language comprehension and film segmentation have demonstrated the powerful effects that the presence of boundaries can have on subsequent memory performance. Moreover, memory performance for what came next is poorer when what came next occurred after a boundary (Ezzyat & Davachi, 2011; Zwaan, 1996). In addition, items can become bound together based on shared context, and reductions in shared contextual features can also reduce the strength of memory for the associations between items (Howard & Kahana, 2002). In addition to spatial shifts, the effects of event segmentation can also be found in studies of context shifts. For example, Dubrow and Davachi (2013) conducted a study to examine the effects of context shifts on memory for sequential order. Participants were presented with lists of nameable objects that used images of celebrity faces as boundaries between the nameable objects. Participants were tested for recency discriminations and performance was poorer if the probed objects came before and after the image of a face. In addition, the greater the time gap between probed objects the better was participants' performance on judgments of temporal order. A short temporal gap, with no intervening change in picture type, resulted in the best performance on sequential order judgements.

Previous studies have shown the disruption of memory for temporal order due to spatial gaps and temporal gaps; the effect can also be found with a change in context represented by different categories of colour pictures. In a study on the effects of context-shifts, Dubrow & Davachi (2013) directly compared memory for the temporal order for objects across a boundary in two separate events, to memory for objects occurring within a single event between boundaries. Memory for temporal order was found to be disrupted when objects were split into two separate events. The result could be due either to the boundary causing an impairment or the grouping of objects between boundaries causing an improvement. Furthermore, the context boundaries did not result in an improved memory for the items immediately before or after the boundary, as would have been predicted by Event Segmentation Theory (Kurby & Zacks, 2008; Swallow, Zacks & Abrams, 2009; Zacks, 2020). While boundaries defined by doorways, spatial gaps and context shifts have been interpreted as driving segmentation, a further possibility is that memory performance may be influenced by temporal clustering without the need for definite boundaries between clusters.

2.6 Time

Although life is experienced as a never-ending flow of events, the contents of human memory are composed of temporally discrete episodes. How is the concept of continuous time segmented and organised such that one moment of time may be distinguished from the next? Several studies have examined the effect that temporal or contextual shifts have on subsequent memory performance (e.g., see Dubrow & Davachi, 2014; Davachi & Dubrow, 2015; Dubrow & Davachi, 2016; Horner *et al*., 2016). Event Segmentation Theory proposes that memories for events are formed when our predictions about what will happen next does not match with reality (Zacks, 2020). However, previous work on reading comprehension has shown that informing participants about what is about to happen does not prevent the segmentation of events from occurring (Pettijohn & Radvanksy, 2016). A central question for the present thesis is to distinguish between the contributions that the presence or absence of prediction errors that may be driven by the presence of doorways have on driving segmentation that influences memory performance. In addition, many studies on event segmentation have made use of tests of recognition (Swallow, Zacks & Abrams, 2009; Radvansky, Tamplin & Krawietz, 2010; Radvanksy & Copeland, 2006; Newtson & Enquist, 1976) which could be missing out on information about memory for temporal and contextual sequences. The experiments reported in this thesis present segmented sequences of word lists, and test memory with free recall to reveal the effects of segmentation on memory for temporal order and temporal clustering for remembered sequences.

An improved memory performance driven by the segmentation of events can be found due to the presence of predictable temporal clustering (Schapiro *et al*., 2013). Rather than prediction errors, the segmentation of events could be due to context-shifts or no more than the pauses between moments. Episodic memory contents are formed of distinguishable events; however, episodic memory also holds information about how the events are connected. For example, Ezzyat and Davachi (2011) presented written stories to participants. Comparisons were conducted between sentences that contained the phrase ‘a while later’ or the phrase ‘a moment later’. With equivalent reading time for the sentences, participants showed poorer memory performance when information crossed the phrase ‘a while later’ which denoted an increased gap in time. Similarly, Speer and Zacks (2005) compared the effects of the phrases ‘a while later’ and ‘an hour later’. The study produced a greater reduction in memory performance for the words encountered immediately before the phrase ‘an hour later’. Simply describing a longer period passing produced a larger deficit in memory performance. This finding is important because it suggests that the segmentation of events could be entirely dependent on the pauses between moments, rather than spatial-gaps, walking through doorways or context-shifts.

One interpretation for an improved memory performance within events compared to across events is that retrieving the event boundary also retrieves the information that was temporally synchronous within working memory prior to experiencing the boundary. Support for this view comes from a study by Kahana (1996), who demonstrated improved memory performance for information experienced close in time. One interpretation of this temporal clustering effect is that items appearing close in time share a greater contextual overlap. According to this account items appearing further apart in time are separated due to a decreased contextual overlap (Howard & Kahana, 2002). Furthermore, memory retrieval has been linked with the reinstatement of contextual detail (Manning *et al*., 2011), suggesting that contextual details can be used to prompt retrieval of the next event in the stored memory sequence. As an example, when tasked with recalling short word lists, participants will tend to recall the words in a similar order to the order of initial presentation (Postman, 1971, 1972). There are several possible theoretical accounts of the contiguous structure of memory describing how memory for events are ordered in time. One such account is the Temporal Context Model (Howard & Kahana, 2002). According to this model stimuli that appear close in time share a contextual overlap and are grouped in memory without the need for explicit event boundaries, a possibility to which I will return to in the overall conclusions of the thesis. For present purposes, the key point is that temporal clustering could provide an alternative to the prediction errors proposed by Event Segmentation Theory.

The presentation of segmented events has also been shown to influence the experience of time. For example, Fenerici *et al*. (2020) presented filmed scenes and asked participants to make estimates of how long each scene lasted. The scenes either displayed characters moving through doorways (spatial shifts), or characters moving without passing through doorways. Time estimates made at retrieval were found to be longer for scenes that contained spatial shifts than for scenes that did not contain spatial shifts. One interpretation of these data, from the perspective of Event Segmentation Theory, is that the spatial shift experienced when passing through doorways provokes a prediction error that acts as a temporal marker for memory. However, an alternative explanation is that the experience of time may be driven by context drift and perceptual moments of change that are not specifically dependent on the concepts of space and time or prediction errors (Buzsaki & Tingle, 2018). I will now report the current principles of Event Segmentation Theory.

2.7 Event Horizon Model

Having reviewed studies outlining the effects of segmentation via the presence of boundaries I now turn to the current theory of event segmentation represented by the Event Horizon Model (Radvansky & Zacks, 2014; Radvansky, 2012). As noted above, event segmentation is thought to be an account of the cognitive processes involved in creating events and segmentation studies have demonstrated reliable effects on memory performance. The Event Horizon Model (Radvansky & Zacks, 2017) provides a structure for the creation, organisation and storing of events, based on 5 principles:

1: Continuously received information is segmented into event models.
2: The event model that is currently active is held within working memory.
3: The primary means of organising events are the causes and effects that connect them.
4: Information split across multiple events is better remembered.
5: There is interference for recalling information across competing events.

As noted previously, to allow memories to be formed the flow of information encountered throughout life must be parsed into discrete events, and the first principle seeks to describe how this parsing process occurs. According to the Event Horizon Model, moment to moment predictions are formed about what will happen next, based on the current event model. If the prediction proves to be incorrect an event boundary is experienced and the current event model is updated. Previously discussed studies of Event Segmentation Theory

(Kurby & Zacks, 2012; Swallow, Zacks & Abrams, 2009) provide an account of the components that are required to provoke a prediction error, with a particular interest given to spatial gaps, temporal gaps, context shifts and passing through doorways as means of provoking a prediction error. The second principle states that the current event model is held within working memory, whereas the previous event model has either been lost or has been encoded into long-term memory, accounting for the effect of an improved memory performance for currently held items when compared to memory for recently dropped items (Pettijohn & Radvansky, 2016; Radvanksy & Copeland, 2006). The third principle describes the memory benefits for sequences of causally connected material (Radvanksy & Copeland, 2001). The fourth principle describes the benefits of segmentation as a means of chunking information to allow for an increase in the number of items that can be recalled. Memory for list items is better when the lists are split across multiple events (Pettijohn, Thompson, Tamplin, Krawietz & Radvanksy, 2016). Finally, the fifth principle describes an interference effect if participants are asked to retrieve a single event from multiple overlapping events that share common features.

As the preceding review makes clear, Event Segmentation Theory provides an account of the robust effect that encountering boundaries between events has on subsequent memory performance. Event segmentation has been proposed as a process of working memory that involves the transfer of information from working memory into long-term memory (Richmond, Gold & Zacks, 2017; Radvansky, 2017). The principles underlying event segmentation could potentially be employed to improve memory performance by providing segmented events during learning. A great deal of work has been done on the topic of working memory, including how much information can be held within working memory. It is only recently, however, that segmentation has been characterised as a working memory process (Radvansky, 2017). While working memory can be thought of as a system that serves multiple functions for the temporary storage and manipulation of mnemonic representations, segmentation may be a fundamental process of working memory that allows streams of information to be formed into memory packets. Richmond, Gold & Zacks (2017) focused on findings that demonstrated the superior memory performance of individuals who agreed with the majority of a group as to when event boundaries occurred. By contrast, individuals that did not experience the same event boundaries as the majority of a group showed poorer memory performance. These findings suggest that the normative segmentation of information could effectively be described as chunking. If appropriate boundaries cannot be identified, then subsequent memory performance will be impaired. Thus, providing appropriate boundaries for individuals could serve to improve memory performance.

From a theoretical perspective Event Segmentation Theory seeks to explain the interactions that occur between working memory and episodic memory. The theory also provides a way to define long-term memory: event boundaries demarcate the beginning and end of an event that can be maintained within working memory and experiencing an event boundary causes the information that is held in working memory to be encoded into long term memory. Thus, from this perspective, if an event boundary has been experienced then tests of memory are necessarily testing information that has already been encoded into long-term memory. The studies of walking through doorways support this interpretation (Pettijohn *et al*., 2017), as do the studies of written stories (Rinck & Bower, 2000) and studies of memory for objects in films (Swallow *et al*., 2009). Participants show poorer memory performance after several types of boundary: a spatial gap, a temporal gap, walking through doorways or after a context shift. While studies have led to the conclusion that each of these types of boundary is important for segmenting information, based on existing evidence it is unclear whether event boundaries require multiple components or can be defined by temporal gaps alone, which is a central question of the present thesis. Nevertheless, event segmentation has been proposed as a fundamental process of working memory, and I explore this proposal in the experiments reported in this thesis. To provide further background for these experiments, next I examine the current accounts of the theories and capacities of working memory, with particular emphasis on the processes of chunking that have been demonstrated in studies of working memory.

3. Working Memory

3.1 Origins

Throughout the ages there have been many theories on the processes, structure and limitation of human memory. Returning to the beginning of the current thesis there is an initial definition of memory: “There are two kinds of memory, he continues, one natural, the other artificial. The natural memory is that which is engrafted in our minds, born simultaneously with thought. The artificial memory is a memory strengthened or confirmed by training. A good natural memory can be improved by this discipline and persons less well-endowed can have their weak memories improved by the art” (Yates, 1966, p. 20). During the era of the ancient Greeks, memory was thought to be composed of two distinct types. While the notion of separable memory systems has gone in and out of favour over the years, in the present day there are well established theories of memory systems with separable components. The ability to hold and manipulate information within mind at the present moment, such as the words within the current sentence, can be defined as working memory (Baddeley & Hitch, 1974; R. Logie, Camos & Cowan, 2020). In contrast to episodic memory, which is dependent on the encoding, storage and retrieval of long-term memories for autobiographical events, working memory can be thought of as a temporary mental workspace with limited capacity that can allow for moment-to-moment maintenance and manipulation of the representation of current events. Before further discussions of current theories of working memory, I will first establish the historical origins of working memory theory. I will then outline current definitions of capacity limits, which are of central interest to the current thesis.

Following the description of two forms of memory defined by the ancient Greeks, a later definition can be found in the works of John Locke (1690) and William James (1905). Locke wrote on the contemplation of ideas and described the retention of information as a faculty of the mind that is done in two ways, a temporary workspace that can hold an “idea in view” and a longer lasting “storehouse of ideas”. Similarly, James discussed the notion of the specious present as “primary memory” and a longer lasting storehouse as “secondary memory”. Later work by Waugh and Norman (1965) detailed primary memory as a limited capacity system and verbal rehearsal of information was interpreted as a means of transferring information from primary memory into secondary memory. From several timepoints throughout history descriptions may be found of two types of memory, one temporally limited in the present and involved in contemplation (artificial, holding ideas in view, primary memory), the other a longer lasting storehouse (natural memory, storehouse of ideas, secondary memory). The detailed definitions of types of memory and the notion of transfer between memory types continues to be a subject of debate within current cognitive theories. In particular, the different theoretical accounts of how information is transferred between distinct types of memory is a central interest of the current thesis and it is a notion that I will return to in the empirical chapters.

Building on the ideas of primary and secondary memory, Atkinson and Shiffrin (1968) established a highly influential 'Modal Model' of memory. The model consisted of three major components, a sensory register, a short-term store and a long-term store. The model regarded the short-term store as a form of working memory, with limited capacity that could be used to temporarily hold and manipulate information. According to this view information passes through the sensory register and into the short-term store. Information maintained within the short-term store could be encoded and subsequently retrieved from the long-term store. In a later paper, Atkinson and Shiffrin (1971) expanded the concept of working memory as a system for making decisions, solving problems, and directing the flow of information to and from the long-term store. One important feature of the Modal Model is that it is explicit that interactions between the short- and long-term store are crucial for long-term learning to occur.

Although highly influential for current accounts of memory, there are inherent limitations to the Modal Model when it is used to describe how learning occurs. From an empirical perspective research has shown that simply maintaining information within a working memory system does not necessarily result in long-term learning (Craik & Watkins, 1973; Bjork & Whiten, 1974). Rather than maintenance supporting the transfer into long-term memory, the Levels of Processing theory (Craik & Lockheart, 1972) proposed that long-term learning depends upon the nature of the processes conducted with maintained information. According to this view stimuli that are processed on image alone will be poorly retained, whereas naming and describing the images would improve memory performance, and performance could be further improved by creating semantic associations. Depth of processing, rather than the duration of maintenance, was then crucial for long-term learning, emphasising that simply holding information within a short-term store is not enough to account for long-term learning. A further alternative that will be explored in the present thesis is that rather than depth of processing, the presence of event boundaries may be crucial to support long-term learning.

A further precursor to current theories of working memory can be found in Dual-Coding theory (Paivio, 1971) which proposes two separable channels, one that deals with language and one that deals with imagery. These dual channels take information from sensory inputs, information can then be transferred between channels, before being sent to output systems. The information present in each of these channels may or may not be experienced consciously. Dual-Coding theory proposes two interacting yet functionally independent stores for holding verbal information and for storing images. These dual channels can be engaged either automatically or with purposeful thought, and making use of both will allow for more effective storage and retrieval. Whilst the earlier Modal Model of Atkinson and Shiffrin assumed a general capacity limited working memory, Pavio's Dual-Coding model is distinctive in proposing separable capacities for different types of information (i.e., verbal versus imagery).

There are many studies that provide evidence in support of Dual-Coding theory, with arguably the strongest support coming from studies of 'interference' effects. In these studies participants are asked to carry out two mental tasks at the same time, testing whether performance is affected by the competing task demands. The logic of interference studies is straightforward: if the tasks require the use of the same resources, then task performance will drop, whereas if performance does not drop, then the participant is making use of separate capacities. Multiple studies have conducted various combinations of verbal, imagery, and visual-spatial tasks. Across these studies a clear pattern emerges, with participants performing better if they are given one verbal task and one imagery task than if they are given two verbal or two imagery tasks (Brooks, 1967, 1968; Atwood, 1971; Segal & Fusella, 1971; Baddeley, Grant, Wright & Thompson, 1975; Janssen, 1976, 1976b; Baddeley & Lieberman, 1980; Eddy & Glass, 1981; Hampson & Duffy, 1984; Logie, Zucco & Baddeley, 1990; De Beni & Moe, 2003). Separable capacities have now become a core feature of current theories of working memory, with implications for Event Segmentation Theory in terms of the way in which events are constructed. I explore the issue of how the operation of separable working memory capacities influences the construction of events in further detail within the empirical chapters and general discussion.

As well as accounting for interference effects, Dual-Coding theory provides an explanation for the finding that pictures are better remembered than words alone as both images and verbal labels are available to support memory performance. The Picture Superiority Effect is a well-established phenomenon (e.g., see Kirkpatrick, 1894; Nickerson, 1965, 1968; Paivio, Rogers & Smythe, 1968; Shepard, 1967; Madigan, 1974; Brady *et al*., 2008; Nelson, Reed & Walling, 1976; Paivio, 1991; Paivio & Csapo, 1973). Previous work has demonstrated that pictures are typically better remembered than words, however it is not the case that memory for pictures is always superior to memory for words. In some circumstances memory for pictures can be equivalent to or even worse than memory for words. For example, Oates and Reder (2010) found that memory for abstract images that could not be easily named was worse than memory for words. Testing also revealed that a meaningful word with an image is better remembered than a meaningful word with no image, or an image with no meaning that cannot be named. Taken together therefore, the evidence suggests that pictures are only superior if they can be given a meaningful label (Reder *et al*., 2006; Reder, Park & Kieffaber, 2009), whereas images that cannot be named are less likely to be remembered.

The Method of Loci introduced at the beginning of the current thesis provides an account of memory performance that is supported by Dual-Coding theory. When both verbal and visuo-spatial information is present, memory performance improves. While the Method of Loci is effective for words with low imageability, it is more effective with highly imageable words. Creating associations between words, images, and locations between event boundaries may allow for more efficient transfer of information between working memory and long-term memory, which in turn allows the information to be better remembered. Training in the Method of Loci may enhance the ability to generate the missing parts of a scene regardless of the format of the presented information. Having examined early work outlining separable components of memory I will now explore current theories of working memory, the nature of interactions between working memory and episodic memory, and the potential for employing cognitive theories to improve long-term learning.

3.2 Multiple Components

The Multi-Component Model of working memory was initially developed to account for the weaknesses of the Modal Model of Atkinson and Shiffrin (1968). The way we learn, the way we acquire knowledge, and the way we attend to, manipulate and store information for later retrieval has long been an area of interest within psychology. A key area of research that seeks to define these processes is that of working memory. As should be clear from the preceding discussion, however, multiple definitions of working memory exist within the literature. While the current thesis is not primarily concerned with distinguishing between models of working memory, the current research does examine the interactions between working memory and long-term memory. Therefore, a brief overview of current models of working memory will be provided, before examining how short-term temporary capacity limits influences long-term learning. The first definition that will be discussed is that of multiple dissociable domain specific components for the short-term storage and manipulation of information.

The Multi-Component Model of working memory originally described in Baddeley and Hitch (1974), Baddeley (1986) and revised in Baddeley (2000, 2007) seeks to describe how we temporarily store and manipulate information for thinking and reasoning. The Multi-Component Model describes working memory as a mental workspace that has multiple channels, each of limited capacity, where the information that is currently being manipulated is held. The original multiple components account was comprised of the phonological loop, the visuo-spatial sketchpad and the central executive, with later work leading to the addition of an episodic buffer. The following sections provides a brief overview of each component.

The phonological loop includes a temporary store that can hold phonological information as a memory trace. It also includes a processing component that allows for articulatory rehearsal (Repovs & Baddeley, 2006). The information can only be held for up to 2 seconds and will be lost if it is not constantly rehearsed. While speech reaches the storage component automatically, visual-spatial information must be transformed into a phonological representation via a process of articulation. The store can hold a few seconds worth of information, as such, the shorter the stimuli and the faster a person is able to articulate that item the more items can be maintained in working memory. Evidence in support of this view comes from Hoosain (1984) and Stigler, Lee and Stevenson (1986), who conducted studies that compared the digit span of native English and native Chinese speakers. The native Chinese speakers had a span of at least 2 more digits than the native English speakers. The

Chinese characters for numbers are shorter and take less time to articulate than the English characters, which allows for a higher digit span. Information will be lost if it is not maintained, and the speed of articulating verbal stimuli will govern how much information may be maintained.

The visuospatial sketchpad can temporarily store and manipulate visual and spatial information. Later work led to the fractionation of the visual-spatial sketchpad into separate components for visual and spatial information. Evidence for this fractionation comes from studies of brain damaged patients. For example, Della Sala, Gray, Baddeley, Allamano and Wilson (1999) found that some patients exhibit problems with visual information, while others have problems with spatial information. A developmental fractionation has also been demonstrated (Pickering, Gathercole, Hall & Lloyd, 2010), with capacities for different types of information developing at different rates as children grow. Further studies have assessed the fractionation of the visual and spatial components using interference effect paradigms. The design of these studies involves a memory task with the following conditions: a test of visual memory with visual interference, a test of visual memory with spatial interference, a test of spatial memory with spatial interference and a test of spatial memory with visual interference. Examples of this can be found in Della Sala *et al*. (1999); Logie and Marchetti, (1991) and Darling, Della Sala and Logie (2007), revealing consistent evidence that visual interference reduces performance in memory for visual information, whereas spatial interference reduces performance in memory for spatial locations. The multiple components theory of working memory proposes separable short-term capacities for domain specific information. As should be clear from the preceding review, the distinction between phonological, visual and spatial information is similar to the divisions that are drawn within the Method of Loci and Dual-Coding theory.

Another aspect of working memory account is the central executive acts as a director that manages and controls the use of resources, the phonological loop deals with verbal information and the visuospatial sketchpad deals with visual-spatial information and imagery. Introduced in the Multi-Component Model of Baddeley (1986), the central executive component is described as an area of residual ignorance. The central executive is, perhaps, best thought of as a place holder, acknowledging the limitations of the multiple components model and providing a basis for further research. Rather than a single controlling director, the ability to manipulate information held within working memory could instead be an emergent property of multiple interacting networks (R. Logie, 2016). While a brief description of the central executive is included here, the exploration of executive functions falls beyond the scope of the current thesis.

The episodic buffer component of working memory (Baddeley, 2000) was a late addition to the Multi-Component Model, in part to account for the construction of coherent episodes. The episodic buffer is described as a temporary storage system where the information from other components of short- and long-term memory can be integrated into a single event, creating a memory packet that can itself be encoded into long-term memory. According to this view, the primary function of the episodic buffer is to facilitate the binding together of domain-specific information from the phonological loop and the visuo-spatial sketchpad. The binding could also be provided by perceptual grouping processes, such as the Gestalt principles of proximity, closure and common region (Wagemans *et al*., 2012a; Wagemans *et al*., 2012b). Objects presented close together are viewed as a single group, objects that are part of a closed object will be viewed as a single group and objects contained within the same boundary line will be viewed as a single group. Long-term learning benefits from the binding of information to the extent that a single event may be constructed from multiple subcomponents. From this perspective, the episodic buffer is envisaged as a separate temporary storage system that binds information from the phonological loop, the visual-spatial sketchpad and from long-term memory into a single encodable event.

Visual working memory has been shown to be able to hold approximately four features of a specific type, for example alignment or colour. Importantly, however, these features can be further combined with a feature of a different type, allowing participants to maintain a greater total number of features (e.g., see Vogel *et al*., 2001). Further work where participants are tested on whether there are any changes in previously presented array, by Wheeler and Treisman (2002) showed that the features do not need to be bound together in a single object. However, multiple features are better retained when bound within a single object than when they are separated (Barnes *et al*., 2001; Duncan, 1984).

While information maintained within working memory may be encoded into episodic memory, access to pre-existing stored knowledge is required for the construction of meaningful events. The construction of a meaningful event requires information to be present within long-term memory before it can be called into working memory for further manipulation (Barquero & Logie, 1999; Pearson, Logie & Gilhooly, 1999). Evidence against viewing working memory solely as a gateway that information must pass through before entering long-term memory can be found in studies of unilateral spatial neglect, where patients ignore and are seemingly unaware of information presented on their left side. For example, Marshall and Halligan (1988) conducted a study with patient PS who suffered from neglect. Patient PS was presented with images of two houses, the bottom house appeared normal whereas the left side of the house above it was on fire. Patient PS could not tell any difference between the houses. However, when asked which of the houses they would rather live in, they consistently chose the house that was not on fire, despite being unable to explain why. Based on the pattern of behavioural performance, Marshall and Halligan concluded that information about the house being on fire was being processed implicitly, without patient PS being aware of it. If long-term learning required information to first pass through working memory, then Patient PS's choice of house should have been at the level of chance.

The multiple component model proposes that phonological, visual and spatial information can be processed concurrently and independently without interference. In the conclusions of the present thesis, I argue that the traditional Method of Loci described at the beginning of the thesis involves the generation of segmented working memory packets composed of phonological and visual spatial information, or in other words manipulating, combining, and processing distinct types of information within working memory. I will now briefly discuss alternative theories of working memory, including time-based resource sharing and embedded processes with a focus of attention, before outlining working memory capacity limits.

3.3 Time-based resource sharing

An alternative definition of working memory comes from studies outlining the importance of temporal capacity limits. Previous studies have demonstrated a time-based decay of memory (Brown, 1958; Ricker, Vergauwe & Cowan, 2014) as well as showing that temporal grouping can improve memory (Hitch, 2009). The Time-Based Resource Sharing (TBRS) (Barrouillet & Camos, 2015) model proposes working memory as a medium for constructing and modifying mnemonic representations. In TBRS working memory is envisioned as a separate system and does not contain activated long-term memory representations. According to this view working memory representations are lost rapidly once they are no longer required.

Evidence for this view comes from a study by Dagry and Barrouillet (2017) in which participants were asked to memorise a sequence of seven letters for immediate serial recall. After each letter two words were presented, and participants had to decide whether the word represented was an animal. In addition to recalling the letters, for some trials participants were also asked to recall the word. While participants were able to recall a mean of 4.1 letters in the position of presentation, only 1.86 out of 14 words could be recalled. The TBRS model proposes that both short-term storage and processing share a common resource, suggesting that representations may be processed and lost while maintaining to-be-remembered information. Importantly, from this perspective working memory representations are reconstructions (rather than reflecting retrieval *per se*) and successive reconstructions of the same representations may differ from one another.

The TBRS model was built upon initial work by Case (1985), who proposed that mental manipulations depend on a total processing space, with shared limited capacity for short-term storage and processing. In addition to a shared resource space for constructing mnemonic representations, the TBRS model also strongly emphasises the importance of domain general temporal limits. For TBRS, there are no domain-specific capacities for phonological and visual spatial information as proposed by the Multi-Component Model (Baddeley & Hitch, 1986). By contrast, however, TBRS does embrace the existence of an episodic buffer (Baddeley, Allen & Hitch, 2010). While the Multi-Component Model establishes the episodic buffer as a passive store for holding bound representations from working memory, the TBRS model proposes that the episodic buffer is not passive and instead also depends upon shared domain general resources for both processing and storage.

3.4 Embedded Processes

A further alternative account to domain specific multiple components and time-based resource sharing is to define working memory in terms of embedded processes (Cowan, 2010). The Embedded Processes Model consists of a brief sensory store that activates long-term memory. A subset of the activated long-term memory may be maintained within the focus of attention, and central executive processes can control and manipulate the items within the focus of attention. According to this view activated long-term memory may be subdivided, but not in terms of phonological and visual-spatial information as proposed by the multiple components model (Baddeley, 2000, 2007). Rather than information transferring between dissociable modules such as an episodic buffer, memory may be composed of nested subcomponents with a focus of attention operating within an activated portion of long-term memory.

Despite the existence of some differences between the previously discussed models, all current models agree that working memory has limited storage capacity. Rather than being incompatible, perceived differences between embedded processes, multiple components and time-based resource sharing may be due to labelling rather than describing functional distinctions. Furthermore, while traditionally tests of working memory capacity focus on short-term immediate tests of memory, the influence that capacity limits in working memory have on long-term memory is a primary focus of the current thesis. In particular, I ask whether long-term learning will benefit from the presentation of segmented working memory packets, even when delayed tests of memory are employed?

3.5 Capacity limits and chunking

As noted above, although there are competing theories on the structure and functioning of working memory each theory agrees that a defining attribute of working memory is that of limited capacity. The capacity may vary depending on the type of information that is being maintained, and theoretical accounts propose both dissociable domain specific limits and a domain-general limit. Furthermore, models of working memory vary in the way in which capacity limits are conceptualised – they are typically defined in terms of either a set number of slots or as a continuous temporal limit (R. Logie, Camos & Cowan, 2021). The research presented within the current thesis aims to test cognitive theories of working memory by employing the novel approach of examining capacity limits delineated by event boundaries. To facilitate understanding of the potential importance of the quantity of information encountered between boundaries, I will now provide a brief outline of the development of definitions of capacity limits.

An early exploration of capacity limits may be found in an article by William Jevons (1871). Jevons picked up a handful of beans from a jar and threw them onto a table before attempting to identify how many beans were present (without explicitly counting them).

Jevons correctly identified when 4 beans were present, however the magnitude of incorrect identifications increased with every additional bean above 5. Although not finely controlled, the exercise provided an early example of the limited capacity of short-term memory. In a further initial exploration of capacity limits Miller (1956) identified the capacity limit for the short-term retention of information as seven plus or minus two items. The proposed capacity limit of seven was based on three main types of task. Firstly, in tasks of absolute identification, participants were presented with one stimulus at a time and asked to identify the category of the stimulus, such as musical tones or lines pre-defined as belonging to different categories. Participants could only make use of approximately five to nine categories. Secondly, participants were tested on memory span for recalling a random list of words in order and could reliably recall around seven words in order. Finally, in a task known as subitizing, participants can rapidly guess without counting a number of simple objects (such as beans) of up to seven. However, although seven items can typically be immediately recalled, evidence also shows that the capacity can vary as a function of a process known as chunking. Similar to the Gestalt laws of perceptual organisation, chunking can be thought of as a form of data compression where information is organised into meaningful groups. For example, if participants in a memory test are asked to learn a string of digits for later recall, a greater number of digits will be recalled when dividing the digits into groups of four and reading them as dates of meaningful events.

In two particularly compelling demonstrations of chunking, Simon and colleagues (Chase & Simon, 1973; Gobet & Simon, 1998) examined the differences between chess experts and novices for recalling chess positions. The experiments involved memory for positions of chess pieces in meaningful positions, alongside memory for chess pieces in random positions that would be impossible in a game of chess, and memory for basic wooden shapes (such as triangles). The chess experts had a far greater span than the novices for meaningful positions, slightly better for the random positions, but no better for the basic shapes. The chess experts' experience allowed them to chunk the patterns of positions, presumably because they could draw on both stored knowledge and past event sequences to match the chess positions to patterns of chess games stored in long-term memory. Chess masters can hold chess pieces as groups based on stored knowledge of past chess games, while novices are limited to the handful of individual chess pieces that can be held in working memory.

The concept of chunking has also been demonstrated as a hierarchical process. In a report by Ericsson, Chase & Falloon (1980) a participant developed a chunking strategy over the course of several months to remember sequences of digits. Initially improvements plateaued at around 20 digits, reflecting the organisation of the information into several chunks containing multiple digits. To achieve the chunking, the participant made use of their knowledge of the times for athletic races. For example, the current record for running a mile is 3 minutes and 43 seconds, the digits 343 could be combined into a chunk representing 3.43 minutes. Further practice then led to the participant greatly increasing the number of successfully recalled digits to around 80. The proposed interpretation for the improved memory performance was that the participant was generating single chunks of 3 or 4 digits and subsequently generating 'super chunks' of 3 or 4 chunks. Another theoretical interpretation, explored in the present thesis, is that the structure of memory may depend on establishing event boundaries to construct nested event sequences.

Building on earlier studies, a limited capacity of 3 to 5 items, or approximately 4 chunks, has subsequently been identified and replicated with multiple different methods (Cowan, 2001, 2010). The studies included tests such as brief spatial arrays, overt repetitions of to-be-remembered items and presenting sequences of stimuli with unpredictable endings in order to prevent grouping and rehearsal. A capacity of 4 chunks has also been demonstrated by establishing multi-item chunks such as unrelated word pairs. Participants demonstrate an ability to recall 3-5 items whether each item is a single word or each item is a word pair. These studies demonstrate that curtailing rehearsal (in order to provide immediate tests of memory) is a fruitful approach for investigating short-term memory limits – suggesting a lower capacity limit (3-5 items) than that proposed earlier as 7±2. Whilst curtailing rehearsal has challenged the traditional characterisation of the capacity limits it is notable that, from the perspective of the Event Segmentation Theory, the curtailing of rehearsal may act as a boundary and trigger for episodic encoding. From this perspective, therefore, many tests of working memory capacity are in fact tests of episodic recall. Furthermore, working memory capacity limits may depend upon experience and the domain of the to-be-remembered information. I return to this issue below in outlining the current work.

3.6 Working memory training

As the review of the models above highlighted, one widely agreed feature of working memory is that it can be thought of as a mental workspace for the information that is currently being held in mind. Indeed, studies have shown that a high capacity, along with efficiently integrating, manipulating and transforming the information held within working memory, leads to an improved academic performance (Gathercole, Pickering, Knight & Stegmann, 2004), as well as problem solving skills (Logie, Gilhooly & Wynn, 1994) and fluid intelligence (Engel *et al*., 1999). Furthermore, a high working memory capacity has also been linked to creativity and skill at musical improvisation (De Dreu *et al*., 2012). Taken together these findings suggest that working memory is an essential component for creativity and learning, leading many researchers to conduct studies into the possibility of training working memory.

Evidence very clearly shows that deliberate practice in a specific task leads to improvements in the task that is practiced (Campitelli & Gobet, 2011). For example, in a review of studies on chess expertise, Campitelli and Gobet estimated that 3,000 hours of deliberate practice is required to reach the level of master. By contrast, it is theorised that training working memory could potentially result in fundamental improvements on a range of tasks that are not specifically practiced. One such approach described as ‘brain training’, involves focusing on improving fundamental cognitive capacities and processes. Certain forms of brain training have suggested that benefits may be found (Klingberg, 2010). In a study of training and transfer, Morrison and Chein, (2010) trained participants on complex span tasks where verbal or spatial sequences are presented. After four weeks of training participants demonstrated improved performance and the results also suggested that the training benefits transferred to other tests (such as a Stroop task). However, the benefits of working memory training may be the equivalent of improving a skill through practice, learning to play the piano or a new language may be more beneficial than engaging in repetitive working memory training tasks. Whilst debate continues about the potential of working memory training to provide generalisable benefits in learning, here I highlight an alternative approach that focuses on the way in which learners experience information. More specifically in the present thesis I explore the possibility that memory can be enhanced by manipulating the way in which information is presented to match existing working memory capacity.

The present thesis explores the potential of matching the presentation of to-be-remembered information to working memory capacity. Many studies have worked towards determining the distinct capacities of the Multi-Component Model of working memory. For example, Baddeley and Hitch (1974) identified a limit to the quantity of phonological information that may be maintained. With the addition of an episodic buffer to the model, further studies have looked at the effect of presenting combinations of distinct types of stimuli. With separate capacities for phonological, visual and spatial information, presenting combinations of each of these (that can be constructed and held within an episodic buffer) should result in improved memory performance. Past work has demonstrated that phonological working memory can be employed to improve performance on visuospatial working memory tasks (Pearson, Logie & Gilhooly, 1999). For example, in a study employing articulatory suppression, limiting the availability of verbal labelling influenced performance on a visual-patterns test. Participants can make use of verbal labels to support performance on visuo-spatial tasks (Brown & Wesley, 2013).

One approach to improving working memory performance by matching the presentation of information to existing capacities is visuospatial bootstrapping. Visuospatial bootstrapping is a term for the enhancement of memory that can be found when phonological, visual and spatial information is linked together. Previous studies examined the effect of presenting letter (or digits, or words) visually while the participants had to continuously articulate a sequence of unrelated words (or letters, or digits). The continuous articulation was designed to suppress the use of the phonological loop to rehearse, so that the presented stimulus could only be held visually. Studies reveal that performance is typically worse during articulatory suppression, but the ability to recall the stimulus does not disappear entirely (e.g., see Baddeley, Lewis & Vallar, 1984; Landry & Bartling, 2011). By contrast, when phonological information is tied to distinct locations, memory performance is improved. For example, Darling and Havelka (2010) and Allan *et al.* (2017) conducted experiments that presented digits either in the same location, in a linear left to right display, or in a keypad display (of the kind found on a phone or computer keyboard). These studies revealed no difference in memory performance when comparing the linear display to the same location, whereas presenting the digits in a keypad array resulted in improved performance. As there was no difference between one location versus a linear display, the argument was made that the higher performance for the keypad is a result of working memory benefiting from long-term memory for (or familiarity with) the keypad layout.

Although studies have shown that presenting stimuli in a keypad array improves memory, criticisms have been made of the paradigms employed. In particular, natural numbers are inherently represented on a mental number line. It is therefore likely that for the numbers presented in a single location, participants are already picturing them and placing them on a left to right linear line (Dehaene, Bossini & Giraus, 1993; Schneider, Grabner & Paetsch, 2009). If participants are already picturing a number line, then the single location and linear line conditions are effectively the same condition. Also, while a keypad layout is frequently encountered in day-to-day activities it is effectively a grid (with locations that vary along both an x and y axis, as opposed to only the x axis for a linear line). By extension, it seems reasonable to expect that further performance enhancements might be found if the locations include x, y and z axes. Regardless, just as in chunking, the proposal that the locations need to be in a meaningful layout suggests that creating links with semantic knowledge provides an enhancement of memory. Taken together, therefore, the evidence suggests that combining phonological, visual, spatial and semantic information should result in better memory performance than if only some of types of information is available.

3.7 Memory in space and time

The current thesis is concerned with whether long-term learning can be improved by manipulating the presentation of information to enhance episodic encoding. Episodic memory is long-term memory for the events that are experienced throughout life and can be distinguished from memory for general facts held in semantic memory (Tulving, 1972). Episodic memories are for events, composed of what happened, where it happened and when it happened (Nyberg *et al*., 1996) and require processes of encoding, storing and retrieval. Critically, Tulving (1983) determined that for a memory to be episodic, there had to be a conscious awareness of the retrieved memories. In addition to what, where and when, Tulving also proposed an alternative means of distinguishing episodes, that is the storage of spatial and temporal separations between events.

One of the key areas of the brain necessary for episodic memory is the hippocampus. The discovery of the importance of the hippocampus was established by the study of patient H.M. (Penfield & Milner, 1958; Scoville & Milner, 1957). H.M. suffered from extreme epileptic seizures, and the surgery to remove the hippocampus was necessary to cure these seizures. After the surgery H.M. could function normally, but could no longer create new long-term memories. Studies of patient H.M. established the importance of the hippocampus for episodic memory, providing evidence for the separation of functions within the brain. As part of their impairment H.M. also exhibited specific problems with memory for spatial information, such as how to navigate home, reflecting the fact that establishing a location for where an event occurred is a vital part of episodic memory. While the hippocampus is widely accepted as a central part of the neural system supporting episodic memory (Eichenbaum & Cohen, 2001), it is also known to be involved in navigating and creating spatial maps (Eichenbaum, 2017). Consequently, Milivojevic & Doeller (2013) argue that memory and creating spatial maps are intertwined, forming memories involves integrating perceptual and semantic information with inter-connected locations.

While the hippocampus plays a role for spatial information, it has also been shown to play a role for temporal information (Eichenbaum, 2014). However, remembering a meaningful ordering of when events occurred requires a more sophisticated system for segmenting events. Many studies focusing on the segmentation of memories examine recognition memory (Swallow, Zacks & Abrams, 2009; Radvansky, Tamplin & Krawietz, 2010) and ignore sequential and contextual information. Researchers have shown, however, that performance on episodic memory tasks is influenced by changes in context. For example, Clewett and Davachi (2017) presented participants with streams of images, occasionally switching the category of images that were being displayed. At test participants were asked to perform a recency discrimination test between two items that were either within the same category, or from different categories. Participants were better at identifying the order of the images when they were from the same category than if they were from different categories. Similarly, as noted earlier, Kahana (1996) demonstrated that information that is closely linked in time is better remembered than information that is temporally distant. Taken together, these findings provide support for the broader claim that items that appear close together in time benefit from a greater contextual overlap (Howard & Kahana, 2002). Critically, for the purposes of the present thesis, the temporal context model proposed by Howard and Kahana (1996) provides an alternative to Event Segmentation Theory, whereby events are formed based upon clustering in time rather than around distinct markers that segment events.

As noted above, studies of working memory have established separate processing capacities for words, images and locations. Moreover, presenting information to make use of these separate capacities for words and images can improve the number of words and images that can be remembered. Likewise, presenting information to make use of the separate capacities for words and spatial locations can improve how many words and locations can be remembered. For example, McNamara, Halpin and Hardy (1992a) asked participants to learn environments from a map or learn environments through actual experience. For both conditions, participants learned facts associated with the locations after they had learned the locations. For both map learning and direct experience, participants combined non-spatial and spatial information. The studies showed that nearby locations primed one another; participants had faster reaction times when asked about nearby cities (in comparison to cities that were far away). Also, when multiple facts were associated with a specific location the participants had greater difficulty remembering those facts than single facts about distinct locations. The studies of map learning suggest that there is an upper limit to the benefits produced by associating facts with locations. If too much information is associated with a particular location memory performance will suffer.

Studies of map learning support the view that establishing associations between different types of information may provide benefits in terms of the quantity of information that may be remembered. Shimron (1978) conducted a study where people were either asked to read stories associated with a map, or they were asked to create a copy of the map. Participants that were given stories to read performed much better in remembering details about the map, providing evidence that the integration of phonological and semantic information with spatial locations allows for better learning than spatial locations alone. Further studies of map learning (Abel & Kulhavy, 1989; Kulhavy, Stock, Verdi, Rittschoff & Savenye, 1993; Stock, Kulhavy, Peterson & Hancock, 1995) have demonstrated that having a map as well as text about locations on the map improves learning for both the text and the map. For example, Kulhavy, Stock and Caterino (1994) conducted eight separate experiments on map learning and proposed the theory that presenting text alongside spatial locations on a map provides a processing advantage. From a theory development perspective, it is clear that map learning theory was inspired by both the Dual-Coding theory of Paivio (1983) and the interference studies of working memory by Baddeley (1992). Central to each of these theoretical accounts is the idea that there are separate routes for processing different kinds of information and presenting each type of information simultaneously allows for more efficient learning because the different types of information do not interfere with one another.

More broadly, the memory benefits associated with tying to-be-remembered information to a location or associated semantic information can be accounted for by Encoding Specificity Theory (Tulving & Thompson, 1973). Encoding specificity (also known as Transfer Appropriate Processing (see Lockheart, 2010) states that more will be remembered if the surrounding environment during recall of a memory is the same as when it is first encoded. A seminal study demonstrating this principle examined the domain specific memories of deep-sea divers (Godden & Baddeley, 1985). When divers learned a list of words on land, they showed improved recall performance when subsequently tested on land (compared to when tested in the sea). Similarly, when divers learned a list of words in the sea, they showed improved recall performance when they were tested in the sea (compared to when tested on land). Across conditions, these data showed that performance is significantly improved when the same environmental cues are available at both encoding and recall, whereas performance is significantly worse when the environmental cues that were present during encoding are no longer available during recall. The differences in performance also supports the cue dependant theory of Tulving (1974), when a specific cue is unavailable the memory may prove difficult to access.

For the present thesis, accounts such as the Temporal Context Model and Encoding Specificity Theory also help explain why the Method of Loci enhances remembering. Training in the Method of Loci enables the use of imagination to generate visual and spatial information while learning words. Then, at recall, imagining the visual and spatial information will allow more words to be remembered. From this perspective imagination provides a way to fill in the missing information and take advantage of the benefits of overlapping context. Whilst it is clear that traditional use of the Method of Loci involves considerable effort on the part of the learner, in principle it should be possible to present words, images and locations together in a way that does not require the learner to engage in effortful mnemonic techniques. According to this view, memory should be enhanced if information can be presented to participants during learning and recall in a way that inherently combines words, images and locations, but that relies only on perception (and not their imagination). In this case the benefits associated with training in the Method of Loci should be accrued automatically, without requiring any investment in training. A possibility that shall be explored within the empirical chapters.

3.8 Cognitive theories of multimedia learning

In addition to theories of working memory, a concurrent line of multimedia research has also examined the potential of presenting information to make use of separate capacities for processing different types of information. For example, Mayer and colleagues (Moreno & Mayer, 1999; Mayer, 2001) propose several principles that make use of cognitive theories for multimedia learning. These principles are, of course, largely based upon Dual Coding theory (Paivio, 1971) and working memory theory (Baddeley & Hitch, 1974; Baddeley, 1986). As noted above, studies of Dual-Coding suggest that there are separate capacities for representing and processing verbal information and non-verbal information. Words and images are processed separately, and as such, presenting words and images simultaneously may allow for more efficient encoding of information into memory. Each of these channels has a limited capacity (Sweller, 1999) and the learning process involves effortfully filtering, selecting, organising and integrating information. From this perspective presenting information to make use of each channel, within its limits, will allow for more efficient learning. In addition, however, the learner must engage in multiple different cognitive processes to fully benefit from multimedia learning. Printed words can initially be processed within the visual channel and later transferred to the audio or verbal channel. One important issue highlighted by studies of multimedia learning is that if the learner can control the flow of information, then they can maintain the amount of information at a level that is within the capacity of each channel.

As with the Method of Loci, studies of multimedia learning emphasise that to properly benefit from different sources of information, the learner must engage in active processing. For example, if the auditory information channel is overwhelmed, the learner must select associated pictures and words to focus on, whilst trying to disregard additional auditory information. Moreover, to be fully effective, learners must try to match and merge the information with relevant prior knowledge (Mayer, 1999a, 2001; Wittrock, 1989). If only verbal information is presented and the learner does not attempt to generate visual-spatial images, then the learning process will be less efficient. Likewise, distributing to-be-learned information across multiple channels improves learning (Pailliotet & Mosenthal, 2000). Studies of multimedia learning provide evidence in favour of multichannel encoding for words and images in a similar fashion to the way in which working memory studies have established a fractionation of the visual-spatial sketchpad into separate components (R. Logie, 1995). Once again, therefore, the multimedia learning view highlights the fact that presenting words, images and locations together should allow more words to be remembered than when words, images and locations are presented independently. Even more importantly for present purposes, the multimedia approach makes clear that one potential approach to providing efficient learning content may be to present information to learners in a way that makes use of each of these separate capacities and encouraging learners to transform or generate whichever type of information is missing.

As noted previously, the potential for training to generate learning improvements is well documented. For example, Cornoldi and De Beni (1991) compared groups of students trained in the Method of Loci with groups that were not. Those that were trained remembered more of the passages that they were asked to remember and presenting the passage in an audio format was more effective than presenting them as text. One interpretation of these results is that presenting the passage as text made use of visual perception and interfered with the ability to generate visual imagery. By extension, and consistent with theories of multimedia learning, if words are presented at distinct locations around a virtual environment participants should be able to build up a mental map to aid memory performance (by linking word groups with locations). As I outline in more detail in Chapter 4, the broad aim of the current thesis is to test this prediction, assessing whether learning can be enhanced by tailoring the presentation of information to fit the constraints of the working memory system. In doing so I examine whether the benefits of the Method of Loci can be achieved without the costs associated with training, asking whether encountering words at distinct locations within a virtual environment allows for a more efficient encoding of words.

4. Methodological Approaches

4.1 Bayesian analysis

The experiments reported in the current thesis make use of Bayesian analysis rather than traditional frequentist analysis. Null hypothesis significance testing (also known as a 'frequentist' approach) has long been the standard approach for psychological research, however there are several notable drawbacks associated with this statistical method. Wagenmakers (2007; see also Jarosz & Wiley, 2014) lays out the issues of p-values in the frequentist approach and provides information on an alternative in Bayes factor analysis. The following section will attempt to briefly convey the drawbacks and benefits of these approaches. First, p-values cannot be used as evidence in favour of an alternative hypothesis. In fact, the frequentist approach is only gathering evidence against a null hypothesis. A researcher may assume their choice of alternative hypothesis is responsible for an effect when in fact there could be other explanations for the result. If we were to make a statement such as ‘eating apples results in healthy teeth’, under the frequentist approach the most that could be said is given that the null hypothesis can be rejected there is less than a five percent chance that the teeth are in good condition due to something that is not eating apples. However, any statement in favour of an alternative hypothesis has no evidence to support it. Furthermore, the number of participants that a researcher decides to 'stop' the study at has a significant impact on finding a significant result. If a study employs 'optional stopping' they can keep going until they find a significant result that can be published and ignore every case where no significant result was found. A p-value of .05 means that we will find that we are wrong every 1 out of 20. It is as if with every study, we are trying to identify which dice we are rolling and hoping that it is a 20-sided dice where rolling a 1 is the null hypothesis. However as mentioned above if we find that it is let’s say a 10-sided dice ($p=.1$) then we can keep on testing until we find the result that we are looking for.

An alternative to null hypothesis significance testing is the Bayesian approach using Bayes factors also known as 'comparative'. Unlike the frequentist approach which makes no comparisons, the Bayesian approach compares the probabilities of both a null and alternative hypothesis. Bayes factors provide a ratio of likelihoods, whereas a p-value provides no statistical evidence in favour of an alternative hypothesis. Returning to the hypothetical statement above of ‘eating apples results in healthy teeth’, making use of Bayes factors would allow us to make a statement such as 'there is a 10% chance that teeth are healthy because of eating apples'. In addition to providing evidence in favour of the alternative hypothesis, Bayes factors also allow researchers to make much clearer statements that may help communicate results. Furthermore, Bayes factors are not dependent on the number of participants; a p-value of .05 does not mean the same thing with a sample size of 42 or 252 whereas two equal Bayes factors do. Given the advantages associated with the Bayesian approach, statistical researchers have long argued that Bayes factors should be included in scientific reports (as outlined in Dienes, 2008). Another advantage of employing Bayesian analysis is that the accumulating evidence can be explored while the study continues. Bayesian analysis allows a greater freedom for terminating data collection early, making more efficient use of time and funding (for further information on Bayes see Berger & Berry, 1988; Kadane, Schervish & Seidenfeld, 1996; Edwards, Lindman & Savage, 1963; Rouder, 2014; Schonbrodt, Wagenmakers, Zehetleitner & Perugini, in press; Wagenmakers, Morey & Lee, 2016).

A primary focus of the research reported in the present thesis was to determine to what extent memory performance could be improved by providing segmentation. To support the primary focus, the analysis employed Bayesian methods and optional stopping based on the strength of evidence for a difference in the number of successfully recalled words. In addition, while the accessibility and use of Bayesian approaches continues to grow, the frequentist approach remains popular. The terms 'significant' and ' non-significant' are based on the p-value of a frequentist approach. While the Bayesian approach provides strength of evidence and is not tied to determining a boundary which must be passed before the data provide support in favour of the existence of an effect. In the present thesis a Bayes factor of 3 or higher is taken as equivalent to a p-value of 0.05 and the terms 'significant' and 'non-significant' are employed for ease of comparison with a frequentist approach.

4.2 Virtual environments for research

There are benefits to making use of Virtual Reality (VR) for scientific research. VR offers exact control over what is and what is not presented, along with how information is defined and separated in space and time. In addition, studies conducted within VR can produce the same results as those found in experiments conducted within real environments. For example, Jaroslawska, Gathercole, M. Logie and Holmes (2015) conducted a study that examined the role of working memory for following instructions within a virtual school. The study included a comparison between the virtual school and a real school, and the same results were found in both cases. Similarly, Rose, Attree, Brooks, Parslow and Penn (2010) examined the transfer of training on a simple sensorimotor task in VR, compared to training in a real environment. Training in VR was equivalent to, and in some cases better than, training in a real environment. In contrast to traditional psychology methods, VR can provide detailed control over first person episodic experiences, as well as being an automatic and flexible method of data collection.

Based on the theoretical accounts reported in the previous chapters, I first created an innovative event sequencing virtual environment. Further details of the environment may be found in the following experimental chapters, however here I first provide a brief description. As shown in Figure 1, the environment consisted of a series of virtual rooms, with the rooms being independent modules that could be arranged in different orders (determining the journey that participants travelled through). Within each room, stimuli (i.e., to-be-remembered items) could be presented in a random order, at random locations on a 4 by 4 grid (as shown in Figure 1). In effect, the environment allows for the presentation and manipulation of event boundaries – encouraging participants to segment the ongoing series of events depending on the availability of phonological, visual and spatial information, generating packets of information within working memory for transfer into long term memory. Critically, the use of VR allows for fine control over the way in which participants experience the information, allowing us to investigate how memory performance may vary based on both a) the components required to define boundaries that produce segmentation, and b) the quantity and type of information presented between boundaries.

The event sequencing virtual environment consisted of a square room that contained a 4 by 4 grid for the presentation of to-be remembered information. Each room was a separate module and multiple rooms could be arranged in any order, although for the experiments reported in the present thesis all used the fixed layouts displayed in Figure 2 and Figure 12. A pre-defined list of stimuli could be presented in a specific order and location, or in a random order and location. The present thesis employed word lists consisting of forty words for each condition, so that participants were always presented with a total of eighty words. Each word list could then be further segmented within each virtual room, and the components employed to segment rooms could be manipulated, such as including or removing doorways. Further details of the use of the virtual environment is provided in subsequent experimental chapters.

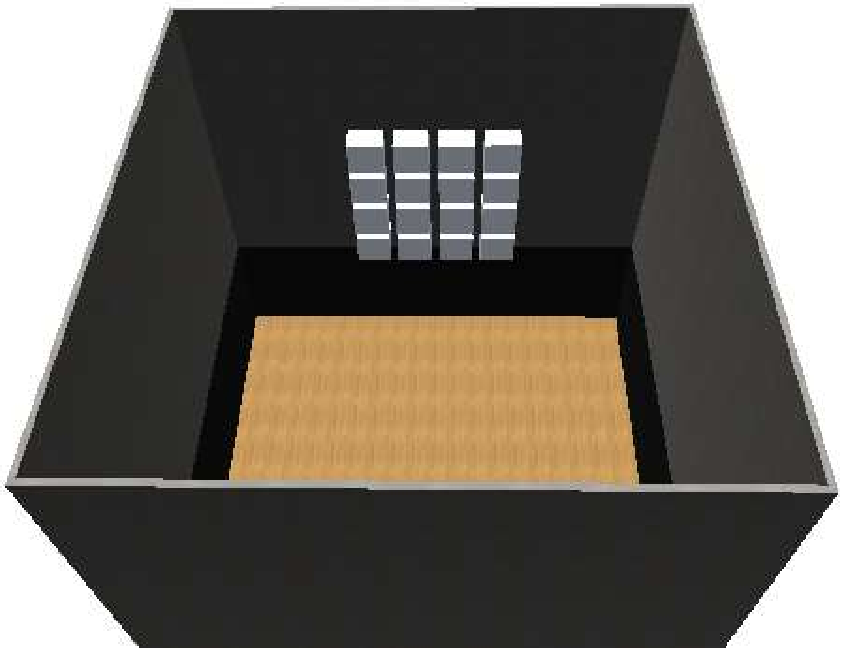

Figure 1: A single room within the virtual learning environment created in Unity3D. The virtual environment allowed for control over the number of rooms and the number of stimuli presented within each room as well as the sequence of left and right turns that were encountered. The environment also allowed for the manipulation of components used to provide segmentation such as the presence or absence of doorways between rooms. Within each module, the words appeared sequentially, in a random order and at random locations on the grid.

4.3 Aims

Across a series of experiments, participants were invited to take part in tests of memory for word lists. The studies involved the use of a custom virtual learning environment to explore the effects that segmentation (provided by event boundaries, defined by doorways and spatial and temporal gaps) has on subsequent memory performance. In broad terms, the current research is inspired by the Method of Loci and aims to investigate whether prediction errors proposed by Event Segmentation Theory are crucial for providing segmentation that supports long-term learning. Are prediction errors a necessary component for defining event boundaries? The research also aims to make use of a virtual learning environment to optimise episodic encoding, to contribute to theoretical understanding of working memory capacity limits and the nature of the interactions between working memory and episodic memory.

The primary aims of the thesis are to investigate the influence that segmentation has on the interactions between working memory and episodic memory. Are the event boundaries proposed by Event Segmentation Theory necessary for long-term learning to occur? To what extent can episodic encoding be optimised by segmenting working memory packets with event boundaries? Do event boundaries act as triggers for episodic encoding and are prediction errors crucial for defining an event boundary? Will presenting packets of information, that can be maintained within working memory, segmented by event boundaries, provide memory benefits in terms of quantity, clustering and temporal order? Given the existing findings outlined in Chapters 2 and 3, I predict that matching the packet size (i.e., the amount of information presented between event boundaries) to working memory capacity will allow long-term memory performance to be optimised. The primary aims may be summarised as follows:

1: To determine whether presenting segmented working memory packets within a virtual Method of Loci can provide a memory improvement effect without training.

2: To identify the importance of prediction errors for defining event boundaries, that may be driven by the presence of doorways and spatial-temporal gaps. Do spatial-temporal boundaries act as a trigger to encode the contents of working memory into episodic memory?

3: To explore a potential goldilocks zone for the quantity and domain of information presented between boundaries. Can episodic encoding be optimised by manipulating the quantity of domain-specific information presented between boundaries?

Chapter 5: Do Doorways Really Matter.
Experiments 1-4.

5.1 Introduction

The experiences of life are composed of a continuous flow of information, the details of which we often struggle to remember later. Cognitive accounts propose that memories of events are encoded, stored and retrieved as distinct episodes (Tulving, 1972; Tulving & Thompson, 1973). From a theory perspective episodic memory is a form of long-term memory that captures individual events, each of which is composed of what happened, when it happened and where it happened. Episodic memory therefore requires individual experiences to be distinguished, for example via the presence of spatial and temporal boundaries between events. The focus of the current chapter is to examine how these boundaries between events influence episodic memory. In broad terms, our aim is to investigate the nature of the boundaries, asking what the essential features of an effective boundary are and whether we can optimise learning by manipulating the presence of boundaries during encoding. Before describing the experiments reported here, we first introduce event segmentation as a conceptual framework for defining the boundaries between episodes.

Event Segmentation Theory describes how the flow of information experienced during everyday life is separated into distinct episodes. Studies have shown that segmentation is an automatic process that acts to organise events (Zacks & Swallow, 2007; Kurby & Zacks, 2008) and supports the transfer of information from working memory into long-term memory (Richmond, Gold & Zacks, 2017; Radvansky, 2017). From the viewpoint of working memory, breaking up information into chunks allows for more efficient organisation, such that more information can be held in mind (Gobet et al., 2001). Consequently, Event Segmentation Theory suggests that it may be possible to optimise episodic memory by imposing clear boundaries at the beginning and end of individual packets of information while they are maintained within working memory. As we explain below, the focus of the current experiments is to examine the effect that boundaries have on episodic memory, by manipulating the number of boundaries, the type of boundaries (spatial or temporal), and the amount of information presented between boundaries. First, however, we outline existing evidence that the presence of event boundaries really does influence subsequent memory.

The segmentation of events has been demonstrated in many different studies (Newtson, 1976; Kurby & Zacks, 2012), using a variety of stimuli including videos and stories. For example, Bailey et al. (2017; see also Zacks, Speer, Reynolds & Abrams, 2009) asked participants to declare when an event boundary occurred, while watching videos of people carrying out everyday tasks (such as making sandwiches or washing a car). During a subsequent test phase, participants were shown short outtakes and asked what happened next. The results showed that memory was impaired when to-be-remembered information occurred after a boundary. Other studies have shown that the effect that event boundaries have on memory depends on when the boundaries are encountered, relative to the to-be-remembered stimulus. For example, Schwaan (2004) investigated the temporal dynamics of event segmentation by deleting sections within a film scene. Deleting points at the boundaries of a scene (i.e., the end of an activity) resulted in impaired memory for the contents, whereas deleting the non-boundaries points within a scene (i.e., in the middle of an activity) resulted in no decline in memory when performance was compared to including no deletions from the film.

The benefits of segmentation have also been investigated using real-world environments, revealing that if items are split across multiple events, they are better remembered than if all the items occur within a single event (Pettijohn et al., 2016; Smith, 1982, Smith & Rothkopf, 1984). These experiments involved presenting a list of words in a single room or splitting the list of words across 2 rooms (each with differing contextual details). The number of words that participants could recall increased when the words were split across 2 rooms. Importantly, these real-world studies showed that walking through a doorway to another room to receive the second half of the list improved memory performance. By contrast, walking from one end of a single large room to the other end to receive the second half of a list produced no improvement in memory performance for the number of words recalled. Although these findings suggest that walking through doorways or contextual changes were the cause of the improvement, the use of real rooms allowed relatively limited control over the spatial-temporal and contextual boundaries that existed between rooms. The current study aims to extend these findings by asking whether event segmentation can be employed to optimise learning when information is presented in a virtual environment, where multiple features can be manipulated and controlled systematically.

Of particular relevance for the current investigation is a demonstration of the disrupting effect of event boundaries within a virtual environment by Horner et al. (2016). Horner and colleagues made use of a virtual environment consisting of 48 connected rooms, each with different coloured wallpaper, separated by closed doors. During learning 2 items were presented in each room as participants navigated through the virtual environment. Upon entering a room, participants were presented with an image of an object, on a table, which they were required to walk up to. After seeing the first object, it would disappear, and a second object would appear on a second table. At test, participants were required to make old or new judgements to a set of previously presented objects and were also asked to identify which object came next. Participants were better at making correct judgements if the objects were experienced within the same room than they were if the objects were from different rooms. Moreover, if the participants had to pass through a door to get to the next object, they found it more difficult to identify which object came next in the previously presented sequence. By controlling the features of the to-be-remembered episodes in a virtual environment, Horner et al. were able to demonstrate that the presence of spatial boundaries directly affects episodic memory for temporal order.

The advantage of having fine-grained control over the presentation of packets of information is also highlighted by demonstrations of individual differences in event segmentation ability. For example, Jafarpour et al. (2019) gave participants movies to watch and asked them to press a button at the start of each new event in order to divide the movie into episodes. After segmenting the movie, the participants were given tests of recognition and recall. Subsequent analysis divided participants into ‘over-segmenters’ (> 1 standard deviation above the mean) and ‘under-segmenters’ (> 1 standard deviation below the mean). The under-segmenters performed better than the over-segmenters in tests of memory for temporal order, whereas over-segmenters performed better than under-segmenters for the quantity of information recalled. The differences between over- and under-segmenters provides evidence for a natural segmentation ability. Critically, these findings also emphasise how important the amount of information and distribution of boundaries is for memory performance. The finding that some individuals naturally segment information efficiently, while others struggle to segment without the presence of distinct external event boundaries, raises the possibility that segmentation (and therefore memory) can be improved through training. According to this view, some individuals are simply less capable of segmenting information when it is presented with boundaries of no or low salience.

The virtual environment used in the current set of experiments was created in Unity 3D (https://unity3d.com), as illustrated in Figure 2. The environment allows participants to be guided through a series of rooms, within which a set of stimuli can be presented for learning. Importantly, the features of the environment can be controlled and manipulated, including both the amount of information to-be-remembered and the spatial and temporal context in which they are presented. Using this virtual environment, we ask what components are required to define a boundary and how much information should be presented between boundaries in order to optimise episodic encoding. The first three experiments make use of the virtual environment to manipulate the components used to define a boundary (gaps in space, gaps in time, and doorways that act as physical boundaries). The final experiment makes use of the same virtual environment to manipulate the number of words presented between boundaries, with the aim of identifying the limits of the memory improvement that splitting information across multiple rooms could provide.

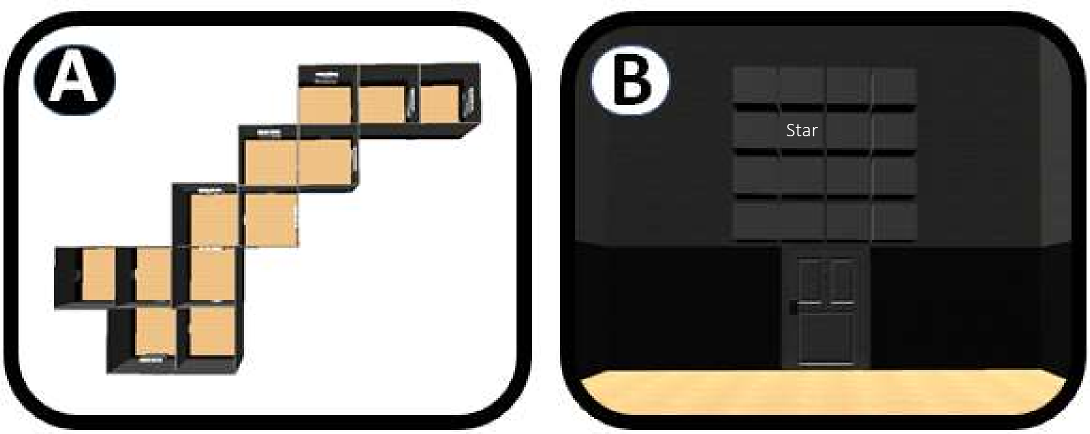

Figure 2: Panel (A) Top down view of the virtual learning environment created in Unity3D. Every room is identical in size, shape, and colour. Movement through the space was automatic, ensuring consistent visual input, with a consistent pace, for all participants. Panel (B) First person view within a room, illustrating the presentation of words to-be-remembered. The virtual environment allowed experimental control over the number of rooms and the number of words presented within each room. Within each location the words appeared sequentially, in a random order and at random locations on the grid.

5.2 Experiment 1

The first experiment sought to investigate whether a memory improvement effect could be observed when words were segmented by spatial boundaries within our virtual learning environment. As is illustrated in Figure 2, each room was coloured a neutral grey, all rooms were the same size and shape, and participants were automatically moved through doorways between rooms. Automatic (rather than self-guided) movement was employed to ensure that every participant experienced the same spatial-temporal gap between rooms, without depending on participants' ability to navigate within a virtual environment. Critically, rather than examining memory for information that crosses event boundaries, our focus is on testing memory for information presented within event boundaries, compared to when no event boundaries were present.

As should be clear from the introduction, although the aim of memory training is to enhance long-term episodic memory, the learning experience inherently requires information to be held in working memory during encoding. Working memory can be thought of as a mental workspace that maintains moment to moment information in temporary storage with limited capacities (Baddeley, 1986, 2000, 2007; Baddeley, Hitch, & Allen, 2021; Baddeley & R. Logie, 1999; R. Logie, 1995; R. Logie, Camos, & Cowan, 2021). As such, it is important that participants are able to hold the to-be-remembered information in working memory. The capacity of the temporary storage was originally defined as seven plus or minus two (Miller, 1956). However, the capacity varies from person to person and can depend on specific characteristics of the items that are being held. More recent studies have shown that working memory typically supports three to five items or chunks of information (Cowan, 2010; Cowan, Morey, & Naveh-Benjamin, 2021). Consequently, in Experiment 1 we compared performance when 40 words were presented within 1 room, to performance when 4 words were presented per room split across a total of 10 rooms. The number of words per room was set at 4 in order to ensure that participants would be able to maintain the information within working memory.

Our approach builds on previous work showing that words split across 2 rooms are better remembered than words presented within 1 room (Pettijohn et al., 2016). Here, because we are examining memory within a virtual environment, we are easily able to generate a series of additional rooms, as required by the design of the experiment. Our primary hypothesis is that memory should be enhanced for words presented across a series of rooms (segmented) compared to a single room (non-segmented). Importantly, use of 4 words per room has the additional benefit of providing 2 boundary words (located in the first and last positions) and 2 non-boundary words (in the second and third position) within each room. We were therefore also able to test a second hypothesis, namely that the benefits of segmentation should be visible as a difference in memory for boundary versus non-boundary words.

Methods

Participants

A total of 17 participants (13 females), with age range 18-23 years (M = 19.7; SD = 1.6) were recruited through the University of Stirling online recruitment portal, and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling General University Ethics Panel.

Materials

The experiment involved a virtual environment presented on a laptop computer (illustrated in Figure 2), created by the first author with the game development software Unity 3D (https://unity3d.com). The environment consisted of a series of identical rooms, each with a single door to the next room that was either on the left, the right or straight ahead. Each room had a 4 by 4 grid directly ahead of the entrance to the room, where words appeared in random locations (cf. Figure 2 Panel B). The experiment involved presenting a series of highly imageable words on the grid. Words of high imageability were used because they ensure good levels of remembering (compared to words with low imageability; see Paivio, 1971; Reder et al., 2006; Reder, Park, Kieffaber, 2009). Presenting a highly imageable word at a location on the grid was used to represent one chunk of information to be maintained within working memory. While one of the aims of the current study was to explore a general capacity limit for the quantity of information between boundaries, we note that future studies can manipulate and draw direct comparisons with the current study: For the quantity of information between boundaries and also the presence of phonological, visual and spatial information as proposed by the multiple component's theory of working memory (Baddeley, 1986, 2000, 2007; Baddeley & Hitch, 1974; Baddeley et al., 2021; R. Logie, 1995; 2011; R. Logie et al., 2021). The current research may also provide a foundation to allow for a more fine-grained exploration of working memory capacity limits and associated episodic encoding due to the presence of event boundaries. The words used in the experiment were taken from the MRC Psycholinguistic database (Coltheart, 1981), and every word had a minimum imageability and familiarity rating of one standard deviation above the mean. These criteria resulted in a list of 421 words, each 3-6 letters in length. From the list of 421 words, 80 words were selected randomly. For the non-segmented condition 40 words were selected at random and presented in a random order, and the remaining 40 were presented in a random order for the segmented condition.

Procedure

Study phase

The experiment involved a study phase with no segmentation, followed by its test phase, and then a second study phase with segmentation, followed by its test phase. As the purpose of the experiment was to determine the potential benefits of externally imposed segmentation, providing the segmented condition first would be the equivalent of instructing participants to make use of mnemonic strategies. Consequently, the non-segmented condition was always given first, thereby minimising the possibility that participants would use a segmentation or mnemonic strategy. Participants were informed that they would be participating in two sets of conditions where they would be required to remember as many words as possible. In the non-segmented condition 40 words were displayed one at a time, in a random order and in random locations, on a 4 by 4 grid within a single room. Each word was displayed for 3 seconds, with a 1 second gap between words. By contrast, for the segmented condition 40 random words were split into 4 packets of 10, displayed one at a time in a random order and in random locations, on a 4 by 4 grid across 10 rooms (i.e., 4 words per room). After 4 words were presented in a room there was a 3 second pause, 6 seconds of moving into the next room and another 3 second pause before the next word appeared. Movement through the environment was automatic so that every participant experienced the same gap in space and time between rooms. The automatic movement also controlled for differences in gaming experience and the ability to navigate in a virtual environment. After the study phase there was a two-minute gap before the test phase, during which participants were asked to count backwards, ensuring that the last words presented were no longer being held in working memory.

Test phase

After each study phase participants were moved into the next room, where instructions were presented for the test phase. During the test phase an empty text box appeared at the centre of the screen and participants typed a word they could remember into the box, then pressed enter, which emptied the text box for the next word to be typed. Participants were not required to type the words in any specific order but were asked to continue until they had typed all the words that they could remember. All the words presented during the study phase and the words typed in the test phase were automatically recorded and stored in a text file to allow for subsequent analysis. After the first test phase the experimenter pressed a button to load the next condition, brief instructions were provided to participants explaining that they would again be presented with a series of words within the virtual environment and asked to remember as many words as possible.

Statistical Analysis

For the analysis Bayesian methods were employed. Statistical tests were carried out with JASP (JASP Version 0.12). Bayesian paired sample t-tests were used to determine the strength of evidence for the alternative hypothesis, or for the null hypothesis. One advantage of using Bayes is that the strength of evidence can be determined. A Bayes Factor (BF) of between 3 and 10 is taken as 'moderate' evidence for the alternative hypothesis, whereas a BF between .33 and .1 provides 'moderate' evidence in favour of the null hypothesis. Furthermore, the Bayes factor has the same meaning regardless of number of participants, unlike p-values (e.g., see Jarosz & Wiley, 2014; Wagenmakers, 2007; Wagenmakers et al., 2016; Wagenmakers et al., 2018 for a complete classification of Bayes factor scores). Adjusted Ratio Clustering (ARC) scores were also calculated using the category clustering calculator for free recall (Senkova & Otani, 2012; Pettijohn et al., 2016). ARC scores provide a measure of how recalled words are clustered by the packets that the words were presented in. The ARC scores are adjusted for the expected chance level. Analysis of Conditional

Response Probability (CRP) as a function of lag was conducted to determine effects of temporal contiguity (Kahana, 1996; Healey, Long & Kahana, 2019). A significant increase in lag+1 represents an increase in the probability that a participant will recall the next item from a forward adjacent position.

Results

The number of words recalled for 40 words presented in one room (non-segmented learning) was compared to the number of words recalled for 4 words per room across 10 rooms (segmented learning). As can be seen in Figure 3(A), memory performance was markedly improved following segmented compared to non-segmented learning. Analysis of the group average data revealed that there was a significant difference in the proportion of words remembered between the non-segmented condition (M = 0.31; SD = 0.09) and the segmented condition (M = 0.47; SD = 0.17). As shown in Figure 3(B), with a Bayes factor $BF_{10} = 339$ the analysis provides 'extreme' evidence that presenting words in packets (across multiple identical grey rooms, segmented by spatial-temporal gaps and the presence of doorways) within a virtual environment leads to an increase in the amount of information that can be remembered.

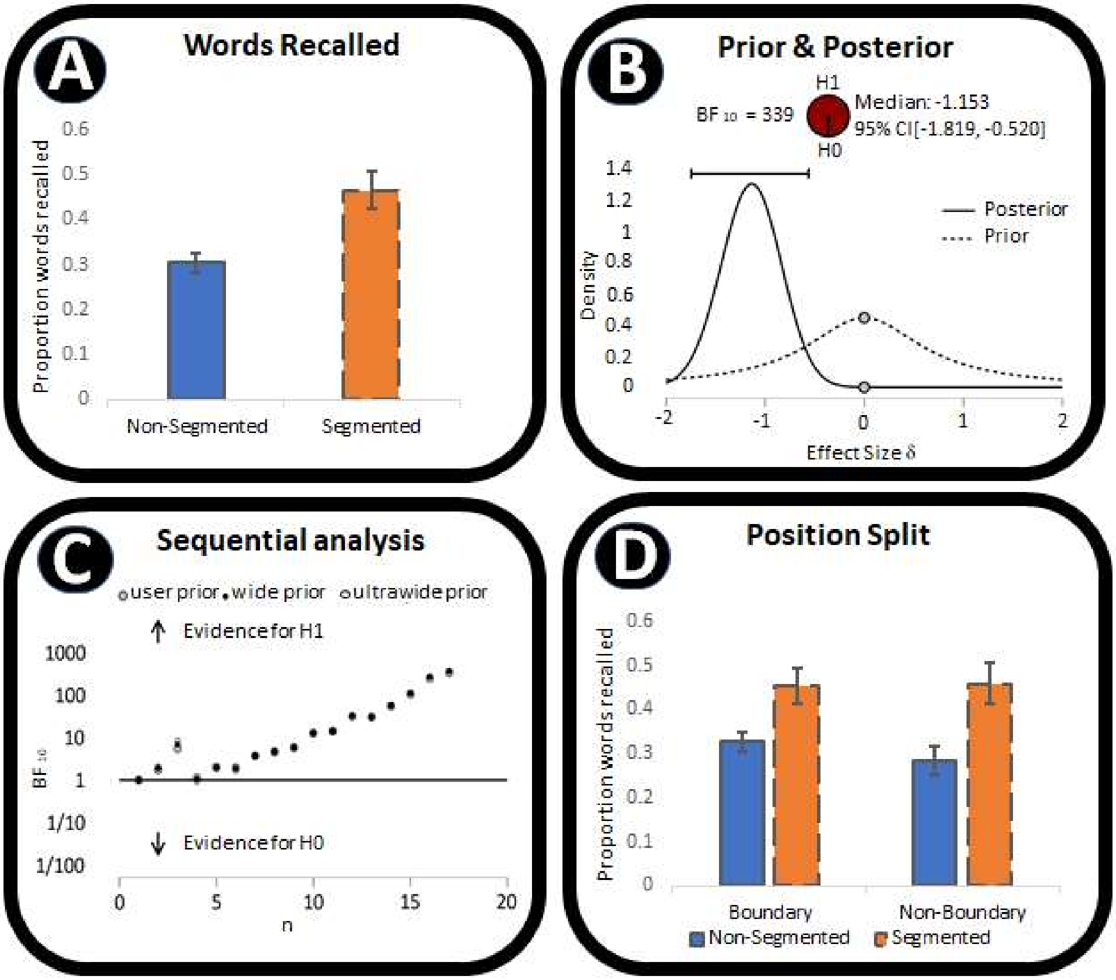

Figure 3, Panel A: Proportion of words recalled following non-segmented (40 words in 1 room) versus segmented (4 words per room across 10 rooms) learning for Experiment 1, showing a clear effect on memory. Error bars represent ± 1 standard error of the mean. Panel B: Bayesian paired sample t-test results, indicating 'extreme' evidence that segmentation led to improved memory (BF_{10}). The density function illustrates the difference in effect size between prior and posterior estimates, and the pie-chart displays the strength of evidence in favour of memory improvement (H1) or no memory improvement (H0). The median effect size and 95% Bayesian credibility interval are indicated in the top right. Panel C: Bayesian sequential analysis illustrates the consistency of findings cross participants. The plot displays how the Bayes Factor changes with each additional participant. Each grey circle represents the data from a single participant, presented in the order of data collection. The smaller dots (defined in the top right) show that the outcome is not dependent on choice of prior. Panel D: Memory enhancement is not specific to items closest to boundaries.

Having demonstrated that memory was significantly improved when the learning environment provided information across multiple rooms, we used Bayesian analysis to examine the build-up of evidence across our participants. As is shown in Figure 3(C), sequential analysis confirms that 15 out of 17 participants provided evidence in favour of the alternative hypothesis. Importantly, the consistency of the outcome across participants also suggests that even if participants were naturally segmenting the information when it was presented in a single room, the imposition of segmentation boundaries within the virtual environment led to a significant improvement. To further investigate the nature of the segmentation effect we carried out two additional analyses, both of which examined whether the structure of the to-be-remembered information influenced memory.

One prediction that follows from Event Segmentation Theory is that the memory improvement reflects a specific benefit for words at the event boundaries, compared to words that are not at event boundaries (Radvansky & Zacks, 2017). If this is the case, within the segmented condition we would expect better memory for boundary words (the first and fourth word in each room) compared to non-boundary words (the second and third words in each room). Figure 3(D) illustrates the pattern of performance for boundary and non-boundary words, revealing a similar pattern regardless of whether to-be-remembered items were presented adjacent to a boundary (1^{st} and 4^{th} items within each room) or occurred between boundaries (2^{nd} and 3^{rd} items within each room). These data were subjected to Bayesian repeated measures ANOVA with factors of segmentation (segmented vs. non-segmented) and position (boundary vs. non-boundary). The Inclusion Bayes Factor for segmentation was $BF_{incl} = 56179$, indicating 'extreme' evidence in favour of segmentation. The inclusion Bayes Factor for position was $BF_{incl} = 0.31$, indicating 'anecdotal' evidence in favour of a null effect for position. The inclusion Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 0.46$, indicating 'anecdotal' evidence in favour of a null effect. For Experiment 1 the results suggest that the improvements provided by segmentation were due to an increase for both boundary and non-boundary words.

Additional analysis was conducted to determine whether the pattern of remembering exhibited clustering, consistent with the structure imposed during encoding, using the Adjusted Ratio Clustering (ARC) method (Senkova & Otani, 2012; Pettijohn et al., 2016). ARC scores are based on the number of recalled items, the number of category repetitions and the number of recalled categories, indexing the extent to which recalled words were clustered by the locations they were originally presented in. The words between boundaries in the segmented condition were compared to words in an equivalent position in the non-segmented condition. Average ARC scores were calculated using every 4 words as a category for both the non-segmented and segmented conditions, revealing a higher degree of clustering when words were segmented during learning (ARC = 0.56; SE = 0.09) than when non-segmented (ARC = 0.24; SE = 0.09), $BF_{10} = 53.7$. This analysis suggests that when structure was introduced (via changes in spatial-temporal context due to moving between rooms) the words that were subsequently recalled were clustered according to the locations in which they were presented during the study phase. The ARC scores therefore provide evidence showing that the words were encoded as a sequence of events, tied to a location and segmented by boundaries.

Finally, Conditional Response Probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words.

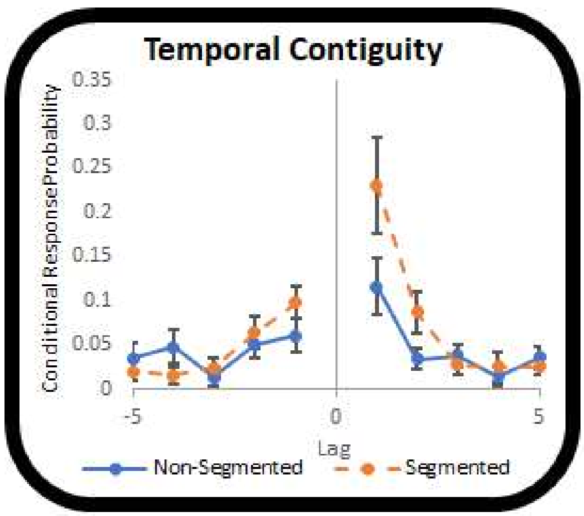

Fig 4: Conditional Response Probability (CRP) as a function of lag. Participants show no significant change in lag+1. Error bars represent ± 1 standard error of the mean.

Analysis of CRP revealed that there was no significant difference in Lag+1 between the non-segmented condition (M = 0.116; SD = 0.129) and the segmented condition (M = 0.231; SD = 0.223). As shown in Figure 4, with a Bayes factor $BF_{10} = 1.528$ the analysis provides 'anecdotal' evidence that presenting words in packets consisting of 4 words (across multiple identical grey rooms, segmented by spatial-temporal gaps and the presence of doorways) within a virtual environment, results in an increase in recalling the words in the order of presentation.

Discussion

We set out to investigate whether a virtual environment can be used to optimise learning, by imposing spatial and temporal boundaries between to-be-remembered words. Consistent with our primary hypothesis, and as predicted by Event Segmentation Theory, in Experiment 1 we found that presenting words within a series of rooms (providing pre-segmented event-boundaries for participants) resulted in a significant increase in episodic recall compared to when the same amount of information was presented in a single room (with no explicit event-boundaries provided). To be clear, even though participants were required to learn equivalent information, the addition of spatial and temporal boundaries during the presentation of the words led to an increase in remembering. As we noted in the introduction, this finding highlights the possibility that virtual learning environments can be used to facilitate remembering. Critically, participants did not have to be trained or directed to encode the boundary information – indeed the boundaries were incidental to the task at hand.

Consistent with our expectations, analysis also revealed that segmentation led to an increase in the clustering of recalled words by location – demonstrating that the imposition of boundaries influenced the order in which participants remembered the words (not just the amount of information retained). This aspect of the data is important because it demonstrates that the changing spatial-temporal context is being encoded into memory. Despite evidence of clustering, and contrary to expectations, there was no evidence that the memory improvement effect was specifically tied to the boundaries *per se*. Event Segmentation Theory (Kurby & Zacks, 2008; Swallow et al., 2009) predicts that the improvement in memory performance should be largest for items presented adjacent to a boundary. Contrary to our second hypothesis, however, analysis of the data boundary position provided no support for the claim that the memory improvement was specific to the first and last words within each room. Whilst Bayesian support for the null hypothesis was anecdotal, the data nonetheless raise questions about which aspects of segmentation are driving the improvements in memory.

Within the wider literature there is clear evidence that boundaries can differ in their salience (e.g., see Ben-Yakov & Henson, 2018), suggesting that an individual's segmentation ability may depend on whether a boundary is recognised as marking the end of an event. In Experiment 1 the boundaries were composed of a spatial gap (travelling between locations), a temporal gap and a physical boundary (provided by walls and a doorway). Although the recalled words are clustered by the locations in which the words are presented, analysis of temporal contiguity revealed no significant increase in memory for temporal order. Previous studies have demonstrated that doorways can disrupt memory for temporal order (Horner et al., 2016). Any benefits to memory for temporal order may be attenuated by the presence of the doorway. The present results led us to question whether individual elements of the boundary could be removed from the virtual learning environment, resulting in memory improvement effects without the presence of doorways.

5.3 Experiment 2

Following the results of Experiment 1, we carried out a second experiment to identify whether the presence of an explicit physical barrier between rooms was necessary to define boundaries and produce a memory improvement. As was noted in the introduction, evidence from splitting word lists across real-world rooms has linked the benefits of segmentation to the physical act of moving between rooms (eg., see Pettijohn et al., 2016; Smith, 1982; Smith & Rothkopf, 1984). However, it may be possible to find the same results from Experiment 1 without the presence of physical boundaries.

We addressed this issue in Experiment 2, using the same environment as Experiment 1, but with removal of the walls and doorways between rooms. Experiment 2 therefore compared participants' ability to remember 40 words presented within a single location (non-segmented), to 40 words presented across a series of 10 locations (segmented). All other aspects of the stimulus presentation and instructions were kept constant, and participants were automatically moved to the next location. Critically, our aim in Experiment 2 was to retain the boundaries formed by spatial-temporal gaps, to test the hypothesis that the benefits of segmentation (compared to non-segmentation) occur even when there is no physical boundary between locations.

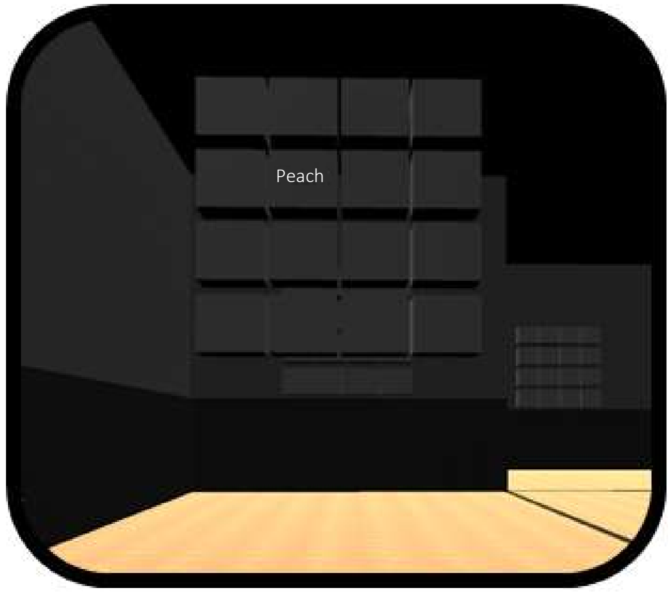

Figure 5: Sample view of the alteration to the virtual learning environment used in Experiment 2, with no physical boundary provided by walls or doorways between locations. Boundaries include crossing a line on the ground, passing beneath the grid, and turning corners.

Methods

Participants

A total of 20 new participants (18 female), with age range 18-36 years (M = 20.2; SD = 4) were recruited through the University of Stirling online recruitment portal, and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling General University Ethics Panel.

Materials

The materials used were the same as in Experiment 1, with the absence of walls and doorways between rooms in the segmented condition.

Procedure

The procedure used was the same as in Experiment 1, with participants automatically moved along the same route, but travelling along an open corridor with a sequence of left and right turns rather than passing through doorways between locations.

Statistical analysis

The analysis used the same measures as in Experiment 1.

Results

The number of words recalled for 40 words presented in one location was compared to the number of words recalled for 4 words per location across 10 locations. There was a significant difference in the number of words remembered between non-segmented (M = 0.28; SD = 0.1) and segmented (M = 0.38; SD = 0.11) conditions ($BF_{10} = 1002$). In this case there is 'extreme' evidence to show that presenting words in packets across multiple locations, segmented by spatial-temporal gaps without the presence of doorways within a virtual environment provides a benefit to the number of words that can be remembered.

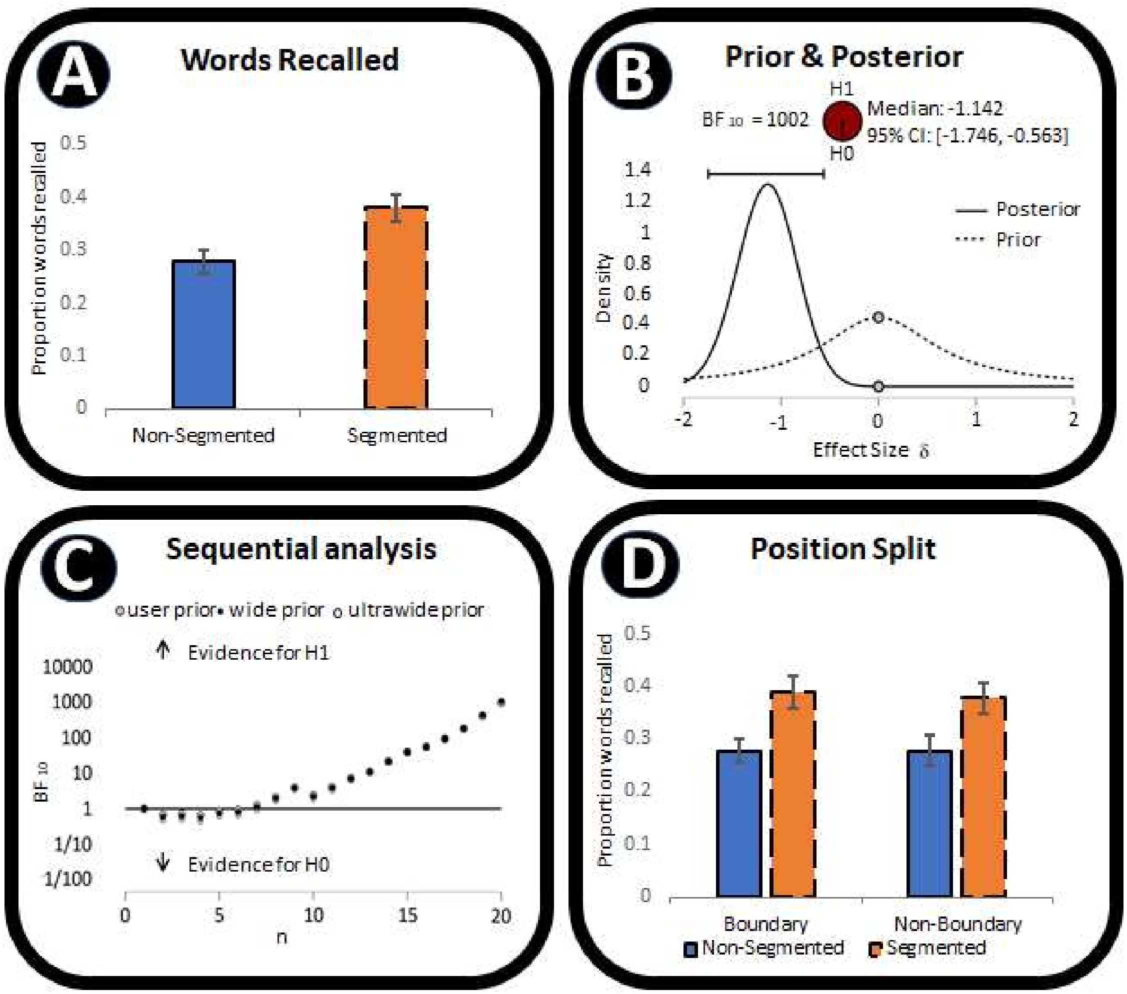

Figure 6, Panel A. Proportion of words recalled for non-segmented (40 words in 1 room) versus segmented (4 words per room across 10 rooms) learning for Experiment 2). Panel B: Plot of prior and posterior. Panel C: Bayesian sequential analysis. Panel D: Memory improvement is not specific to items closest to boundaries.

Experiment 2 demonstrated a significant memory improvement effect when information is split across multiple locations. The results replicated the finding of Experiment 1 and additionally demonstrated that the memory improvement effect was still present even though participants did not pass through doorways. The presence of doorways as used in Experiment 1 is not required in order to produce a memory improvement effect. The Bayesian sequential analysis displayed in Figure 6(C) shows that 18 out of 20 participants provided evidence in favour of the alternative hypothesis. Presenting segmented packets of information leads to significant memory improvement. Further analysis examined whether the improvement was due to boundary words (the first and fourth word presented at each location) or non-boundary words (the second and third words presented at each location). Figure 6(D) displays the recall performance for boundary and non-boundary words. These data were subjected to Bayesian repeated measures ANOVA with factors of segmentation (segmented vs. non-segmented) and position (boundary vs. non-boundary). The Bayes Factor for segmentation was $BF_{incl} = 698$, indicating 'extreme' evidence in favour of segmentation. The Bayes Factor for position was $BF_{incl} = 0.21$ indicating 'moderate' evidence in favour of a null effect for position. The Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 0.24$ indicating 'moderate' evidence in favour of a null effect for the interaction. For Experiment 2 the results suggest that the improvements provided by segmentation were due to an increase for both boundary and non-boundary words.

Average Adjusted Ratio Clustering (ARC) scores were calculated using every 4 words as a category for both the non-segmented and segmented conditions. The ARC scores demonstrated evidence in favour of an increase in clustering from non-segmented (ARC = 0.21; SE = 0.09) to segmented (ARC = 0.53; SE = 0.08) conditions ($BF_{10} = 3.32$). The ARC scores suggest that the words were encoded as a sequence of events, tied to a location and segmented by spatial-temporal gaps. The increase in clustering was still present even when there were no walls or doorways between each location.

Finally, Conditional Response Probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words.

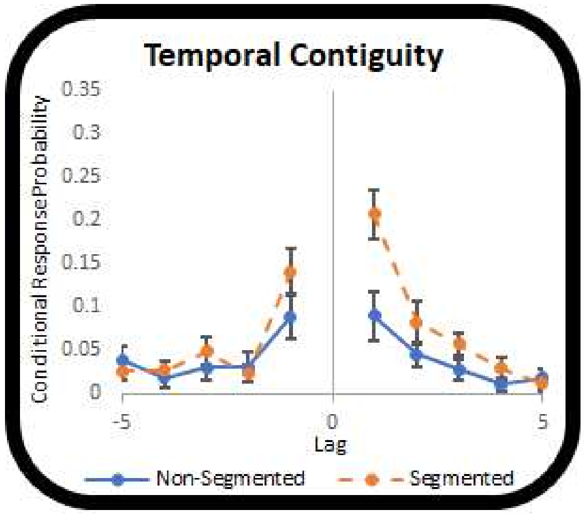

Fig 7: Conditional Response Probability (CRP) as a function of lag. Participants show moderate evidence for an increase in lag+1.

Analysis of CRP revealed that there was a significant difference in Lag+1 between the non-segmented condition (M = 0.09; SD = 0.13) and the segmented condition (M = 0.21; SD = 0.12). As shown in Figure 7, with a Bayes factor $BF_{10} = 5.14$ the analysis provides 'moderate' evidence that presenting words in packets consisting of 4 words, across multiple identical grey rooms, segmented by spatial-temporal gaps, within a virtual environment, results in an increase in recalling the words in the order of presentation.

Discussion

Experiment 2 demonstrated that segmenting lists of words with spatial-temporal gaps results in an increased number of words being available for episodic recall. Consistent with our hypothesis, the memory improvement effect was still present even with the absence of doorways. Previous studies have concluded that the presence of doorways was important for driving segmentation effects. However, the present study provides evidence to suggest that the improved memory performance is not driven by the presence of doorways, the significant increase in memory for temporal order may mean that the memory improvements are driven by spatial-temporal gaps and the presence of doorways may act to disrupt memory for temporal order.

The origins of Event Segmentation Theory can be found in the Gestalt laws of perceptual organisation (Kohler, 1929). Of particular relevance for the current study is the law of common region. Items contained within the same boundary line are perceived as part of the same group even though items on either side of the boundary line may be closer in space. For a real-world example, let us imagine that we are at a sporting event. Crossing a line on the ground which may result in scoring points represents a significant boundary for the segmentation of subsequent memories. In the case of sporting events, stepping across a line on the ground can represent more than simply moving into a different region. However, simply crossing a line on the ground, may be enough to mark the boundaries of a common region and produce a segmentation effect, influencing subsequent memory performance. For the current study the presence of the grid within each location along with the line on the ground and turning corners between locations may be experienced as crossing a boundary line, supporting the idea that all that is required to segment information is the detection of a salient boundary. A segmentation effect can be found with a highly controlled environment, and the addition of richer contextual details for different regions may result in a greater number of participants being able to benefit from the segmentation (even if rich contextual details are not required to find an effect). In our experiments participants are presented with a regular grouping of 4 words per group, providing a predictable rhythm of presentation. In addition to prediction errors that are important for Event Segmentation Theory, a review article by Richmond & Zacks, (2017) outlines alternative mechanisms that may be important for the segmentation of events, including a process of detecting change. On this basis, the segmentation of events may not be due only to the prediction errors outlined in Event Segmentation Theory but more generally due to detecting a salient moment of change as and when the moment is encountered.

Experiment 2 again demonstrated an increase in clustering by location and a corresponding increase in recall performance, confirming that the structure of the to-be-remembered information was being encoded successfully. Experiment 2 also demonstrated an improvement for memory for temporal order, suggesting that the presence of doorways in Experiment 1 was indeed acting to attenuate the memory benefits for temporal order. The presence of doorways may represent an increase in uncertainty as participants are less able to predict what may happen on the other side of the doorway, whereas in Experiment 2 when there were no doorways, participants were better able to predict what would happen next. The result suggests that prediction errors may specifically disrupt memory for temporal order, whereas memory improvement effects, increases in clustering, and memory for temporal order may depend on detecting a moment of change to aid in the segmentation of events. Moreover, as in Experiment 1, the improvement in memory was present for both boundary and non-boundary words. In Experiment 2, however, the Bayesian analysis revealed moderate evidence for the null hypothesis, suggesting that the effects of segmentation really are not tied to items immediately before and after each boundary - an issue that we return to in Experiment 4. More importantly for present purposes, the fact that segmentation effects remain despite the removal of physical boundaries raises the possibility that the segmentation effect could also remain when other boundary features are removed. We address this issue in Experiment 3.

5.4 Experiment 3

In addition to introducing boundaries by moving through doorways, the segmented condition employed in Experiment 1 also included spatial-temporal gaps produced by moving between locations – both of which may have contributed to the effect seen in Experiment 2. Consequently, in Experiment 3 we asked if the temporal gap was, by itself, enough to create a benefit to memory. We therefore repeated our experiment with another cohort of participants, removing the spatial gap from the design. In Experiment 3 participants remained within the same room in both the non-segmented and segmented conditions. Importantly, however, the same temporal gaps used in Experiment 1 and 2 were used as event boundaries. That is, in the segmented condition 4 words were presented, followed by a temporal gap before the next 4 words were presented. We created event boundaries consisting solely of a temporal gap, without participants travelling between locations or walking through doorways. In doing so, we tested the hypothesis that segmentation purely by time would still lead to a memory improvement effect compared to learning in a non-segmented condition.

Methods

Participants

A total of 14 participants (10 female) with age range 18-40 ($M = 21.1$, $SD = 5.7$) were recruited through Stirling University's online recruitment portal and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling General University Ethics Panel.

Materials

The materials used were the same as in Experiment 1, however participants remained within one room in both conditions. The segmented condition employed equivalent temporal gaps for each word packet as used in Experiment 1 and 2.

Procedure

Study phase

The experiment involved a study phase with no segmentation followed by a test phase, and a study phase with segmentation followed by a test phase. In the non-segmented condition 40 words were displayed one at a time in a random order and in random locations on a 4 by 4 grid within a single room. The words were displayed for 3 seconds with a 1 second gap between them. For the segmented condition 40 random words were split into 4 packets and were displayed one at a time in a random order and in random locations on a 4 by 4 grid. After 4 words there was a temporal gap (total of 12 seconds). The temporal gaps were the same as those used in the segmented condition in Experiment 1 when travelling between rooms. After the study phase there was a two-minute gap to allow for some forgetting and so the last words presented were no longer being held in working memory.

Test phase

The test phase used the same procedure as in Experiment 1.

Results

The number of words recalled for 40 words presented in one room was compared to the number of words recalled for 4 words per packet across 10 packets segmented by temporal gaps. There was a significant difference in the number of words remembered between the non-segmented ($M = 0.3$; $SD = 0.1$) and segmented ($M = 0.41$; $SD = 0.16$) conditions ($BF_{10} = 32.47$). The result provides 'very strong' evidence for a benefit to the number of words that can be remembered when segmenting packets of words with temporal gaps.

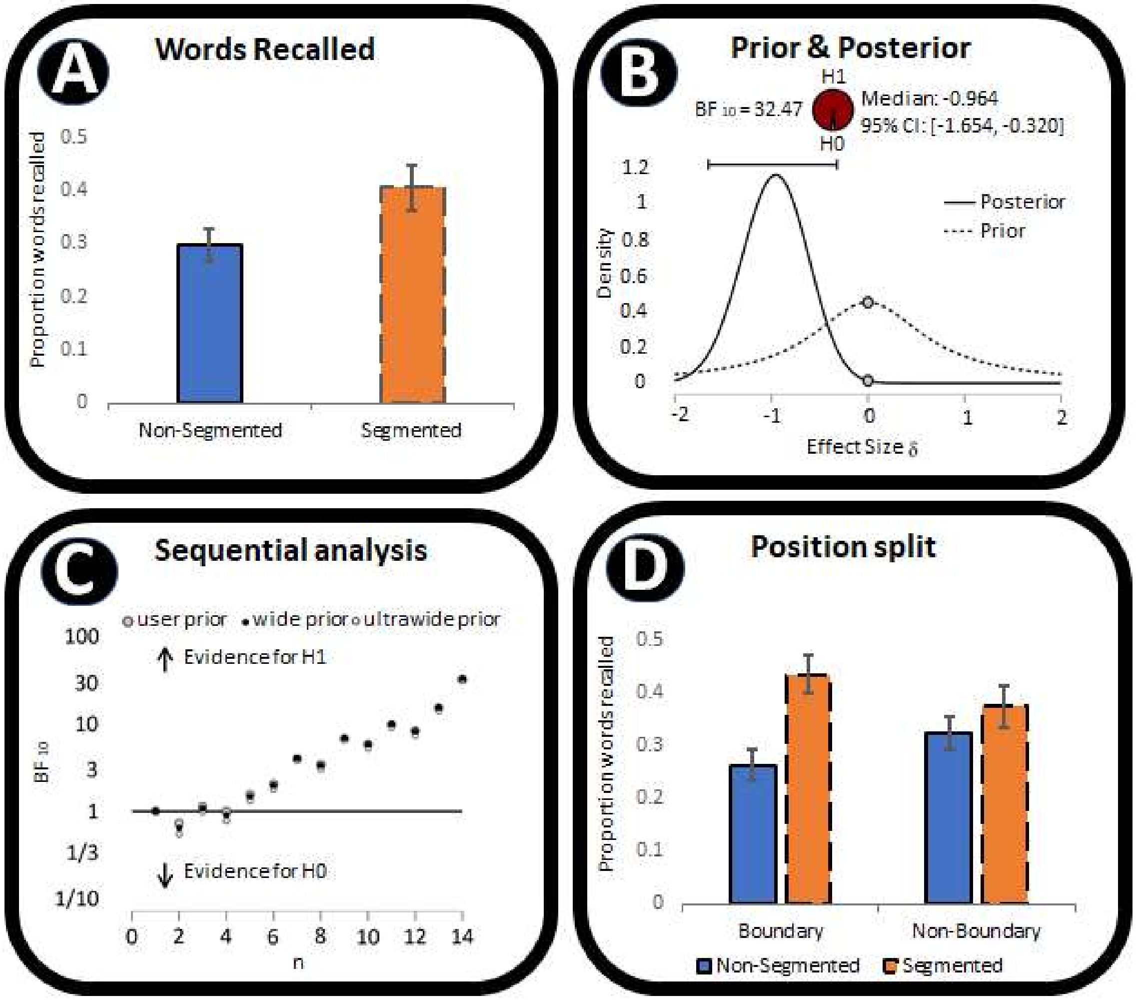

Figure 8, Panel A. Proportion of words recalled for non-segmented (40 words in 1 room) versus segmented (4 words per room across 10 rooms) learning for Experiment 3. Panel B: Plot of prior and posterior. Panel C: Bayesian sequential analysis. Panel D: Memory improvement for boundary and non-boundary words.

Experiment 3 once again demonstrated a significant memory improvement effect when information is split into packets. The memory improvement effect found in Experiments 1 and 2 was still present without participants passing through doorways or travelling through space. The Bayesian sequential analysis displayed in Figure 8(C) shows that 9 out of 14 participants provided evidence in favour of the alternative hypothesis. Presenting segmented packets of information leads to significant memory improvement. Further analysis examined whether the improvement was due to boundary (the first and fourth word presented at each location) or non-boundary (the second and third words presented at each location) words. Figure 8(D) displays the recall performance for boundary and non-boundary words. These data were subjected to Bayesian repeated measures ANOVA with factors of segmentation (segmented vs. non-segmented) and position (boundary vs. non-boundary). The Bayes Factor for segmentation was $BF_{incl} = 64.04$, indicating 'very strong' evidence for segmentation. The Bayes Factor for position was $BF_{incl} = 0.57$, indicating 'anecdotal' evidence in favour of a null effect for position. The Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 1.85$, indicating 'anecdotal' evidence for an interaction. For Experiment 3 analysis using traditional ANOVA suggests that the improvements provided by segmentation were due to an increase for boundary words, however Bayesian evidence reveals only 'anecdotal' support for this conclusion.

As in previous experiments, Adjusted Ratio Clustering (ARC) scores were calculated. There was substantial evidence in favour of an increase from the non-segmented (ARC = 0.14; SE=0.13) compared to segmented (ARC = 0.56; SE= 0.1) condition ($BF_{10} = 8.62$). The recalled words were clustered by the packets, segmented in time, that they were presented in during the study phase. The increase in clustering was present without gaps in space. Words can be clustered by events segmented by temporal gaps without spatial gaps.
Finally, Conditional Response Probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words.

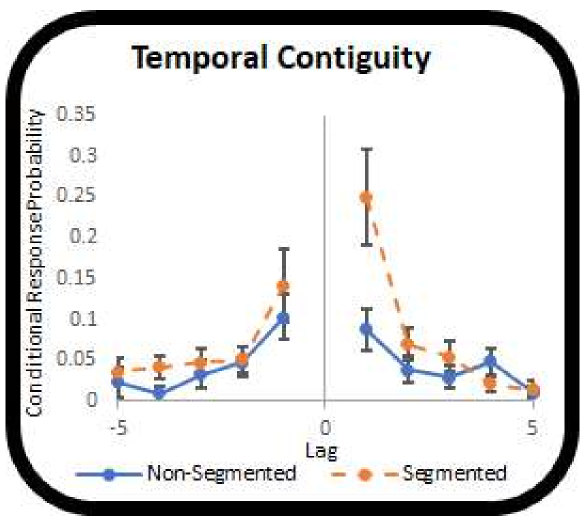

Fig 9: Conditional Response Probability (CRP) as a function of lag. Participants show moderate evidence for an increase in lag+1.

Analysis of CRP revealed that there was a significant difference in Lag+1 between the non-segmented condition (M = 0.09; SD = 0.09) and the segmented condition (M = 0.25; SD = 0.22). As shown in Figure 9, with a Bayes factor $BF_{10} = 6.48$ the analysis provides 'moderate' evidence that presenting words in packets consisting of 4 words segmented by temporal gaps alone within a virtual environment, results in an increase in recalling the words in the order of presentation.

Discussion

The memory improvement effect found in Experiments 1 and 2 were also found in Experiment 3 even though the event boundary no longer included a spatial gap. The Bayesian analysis revealed very strong evidence in favour of our hypothesis that even temporal boundaries provide sufficient structure to benefit memory. As previously, the data also confirm that the structure of the to-be-remembered information was encoded, as evidenced by the similar increase in clustering for both temporal and spatial-temporal gaps. Thus, while physical boundaries and spatial-temporal gaps provided an improvement in memory (Experiments 1 and 2), analysis of Experiment 3 demonstrates that even temporal gaps alone can lead to memory enhancement. The analysis of temporal contiguity again suggests that the presence of doorways in Experiment 1 may disrupt memory for temporal order. We consider the theoretical implications of the segmentation effect in more detail in the general discussion. Here, however, we focus on the pattern of boundary effects. Whilst Experiments 1 and 2 provided no evidence that segmentation effects differ for boundary and non-boundary words, the Bayesian analysis of Experiment 3 revealed anecdotal evidence that the segmentation effects were tied to boundary words.

One potential explanation for the weakness of the evidence for boundary effects seen in Experiment 3 is provided by the sequential analysis, which shows only 9 out of 14 participants exhibited an overall memory improvement effect. According to this account, some participants may have failed to recognise the temporal gaps as a boundary and were therefore unable to benefit from the segmentation. To establish whether the inclusion of participants without clear segmentation effects was responsible for the weakness of the Bayesian evidence for boundary position effects we re-analysed these data, excluding the participants who showed no memory improvement following segmentation. Importantly, however, Bayesian support for the effects of boundary position remained ‘anecdotal’. Taken together, therefore, and in combination with the findings from Experiments 1 and 2, the results consistently suggest that the benefits of segmentation are not specific to boundary words. Experiments 1-3 focused primarily on identifying the relative importance of the presence of physical boundaries, as well as spatial and temporal gaps between packets of words. As noted above, however, across all three experiments the data show that both boundary and non-boundary items benefit from the improvement - contrary to one of the predictions of Event Segmentation Theory (Kurby & Zacks, 2008; Swallow et al., 2009).

Given that the memory improvement effects were found with temporal gaps alone, one alternative explanation could be that participants are allowed additional rehearsal time within the segmented condition. A range of studies has demonstrated that the rehearsal of a list of 4 or 5 words (but not longer lists) for immediate serial ordered recall serves to maintain a single list within working memory (e.g. Barrouillet, Gorin & Camos, 2020). However, several previous studies have examined the potential effects of additional rehearsal on long-term learning of multiple lists and found no benefits. For example, in a study by Tulving (1966) participants were presented with word lists, with one group of participants asked to read each word aloud 6 times. The multiple repetitions of each word made no difference to learning of the word lists. Similarly, Craik & Watkins (1973) specifically examined the potential effects of rehearsal on recall from long-term memory. Participants were presented with words lists, and only asked to rehearse and remember certain critical words within each list. In a subsequent surprise test of memory for every presented word, there was no memory benefit for the words that received additional rehearsal time.

The results from these previous studies suggest that additional rehearsal of items within working memory may aid temporary retention of one short list at a time in working memory but provides no benefit to episodic memory performance for longer lists or multiple lists. In a recent study, Souza & Oberauer (2020) conducted experiments to examine whether rehearsal of six item lists results in improved recall. One group of participants were given training in a rehearsal strategy. The group that received training showed no improvement in recall. In summary, additional rehearsal has been shown to provide no benefits to long-term learning. On this basis, it seems very unlikely that the improvements in episodic memory for the complete list of 40 words that we observed could be explained by the use of rehearsal during the temporal gaps between small groups of words from the complete list. Our own data suggest that episodic encoding does not occur unless a boundary is experienced, and a temporal gap is one such boundary. One implication of our findings is that, for an event to be encoded, participants need to encounter a boundary which includes ceasing to rehearse to-be remembered items. From this perspective, maintaining information within working memory could be described as delaying the experience of a boundary, consistent with the wider claim that episodic memory can be defined as memory for information that occurred prior to the most recent event boundary (Zacks, 2020). If a boundary has not yet been experienced, then the information may not have been encoded into long-term memory. Regardless, of whether this broader theoretical view is correct, previous studies have suggested that additional rehearsal during a gap between lists is unlikely to account for the impact of segmentation that we have observed.

Having ruled out differences in boundary and non-boundary items and the impact of rehearsal as an explanation for enhanced recall performance of segmented lists, we turn to an alternative possibility that follows from the prediction that segmentation supports the transfer of information from working memory into long-term memory (Zacks, 2020). According to this view, failure to find a differential benefit for boundary compared to non-boundary words in Experiments 1-3 likely reflects the fact that participants were able to maintain the words between boundaries within working memory. Consequently, in Experiment 4 we ask whether boundary effects are present when the number of words between boundaries exceeds working memory capacity.

5.5 Experiment 4

Following the results of Experiments 1-3, one final experiment was conducted in order to identify whether boundary effects would emerge if participants were able to maintain the words between boundaries within working memory. To address this question, in Experiment 4 we manipulated the number of words presented between boundaries. Previous definitions have proposed a working memory capacity of 7 plus or minus 2 (Miller, 1956) or as 3-5 items (Cowan, 2010). We therefore compared four lists with 10 words per location, to eight lists of five words per location. Our assumption is that when recalling from a total of forty words, having ten words in each list will exceed the capacity of working memory, and should show poorer recall performance in comparison to five words per list. Consequently, using the same materials as in Experiments 1-3, we compared memory for 5 words per location across 8 locations (close to capacity) to 10 words per location across 4 locations (over capacity). Event Segmentation Theory suggests that the segmentation process involves an updating of working memory. Based on the assumption that the presence of a boundary serves to trigger an updating of working memory, when to-be-remembered packets are small enough to be accommodated within working memory all words should show the benefit of segmentation. By contrast, when working memory capacity is exceeded the benefits of segmentation should be more strongly tied to words presented close to boundaries, whereas items further from the boundary should be less well remembered.

Given the focus of Experiment 4 is solely on working memory capacity the experimental design no longer required a comparison between segmented and non-segmented words. It was therefore critically important to ensure that the segmentation boundaries were salient for all participants. Comparison of the evidence for segmentation effects across Experiments 1-3 reveals that the boundaries imposed in Experiment 2 (based on spatial-temporal gaps) produced the strongest and more reliable memory improvement effect, with the majority of participants exhibiting enhanced performance following segmentation. Consequently, Experiment 4 made use of the same spatial-temporal gaps as Experiment 2 to test the hypothesis that segmentation effects should be greater for non-boundary words than boundary words. Following the theoretical account outlined above, we predicted that when comparing boundary and non-boundary words between conditions the words closest to the boundaries in both conditions will benefit from segmentation. By contrast, when working memory capacity is exceeded, we predicted that the words farthest from boundaries would be less well remembered.

Methods

Participants

A total of 11 participants (6 female; age range 18-28 years: M = 20.2; SD = 2.8) were recruited through the University of Stirling online recruitment portal, and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling General University Ethics panel.

Procedure

Experiment 4 used the exact same procedure as in Experiment 2 with the following changes to the study phase: In the over-capacity condition 40 words were randomly presented at 10 words per location in 4 total locations. In the under-capacity condition 40 words were randomly presented at 5 words per location in 8 total locations.

Results

The number of words recalled was recorded. There was a significant difference in the number of words remembered between over-capacity (M = 0.33; SD = 0.12) and under capacity (M = 0.45; SD = 0.17). Analysis revealed a BF_{10} of 14.41, providing 'strong' evidence that presenting 5 words per location across 8 locations resulted in more words being remembered than 10 words per location across 4 rooms.

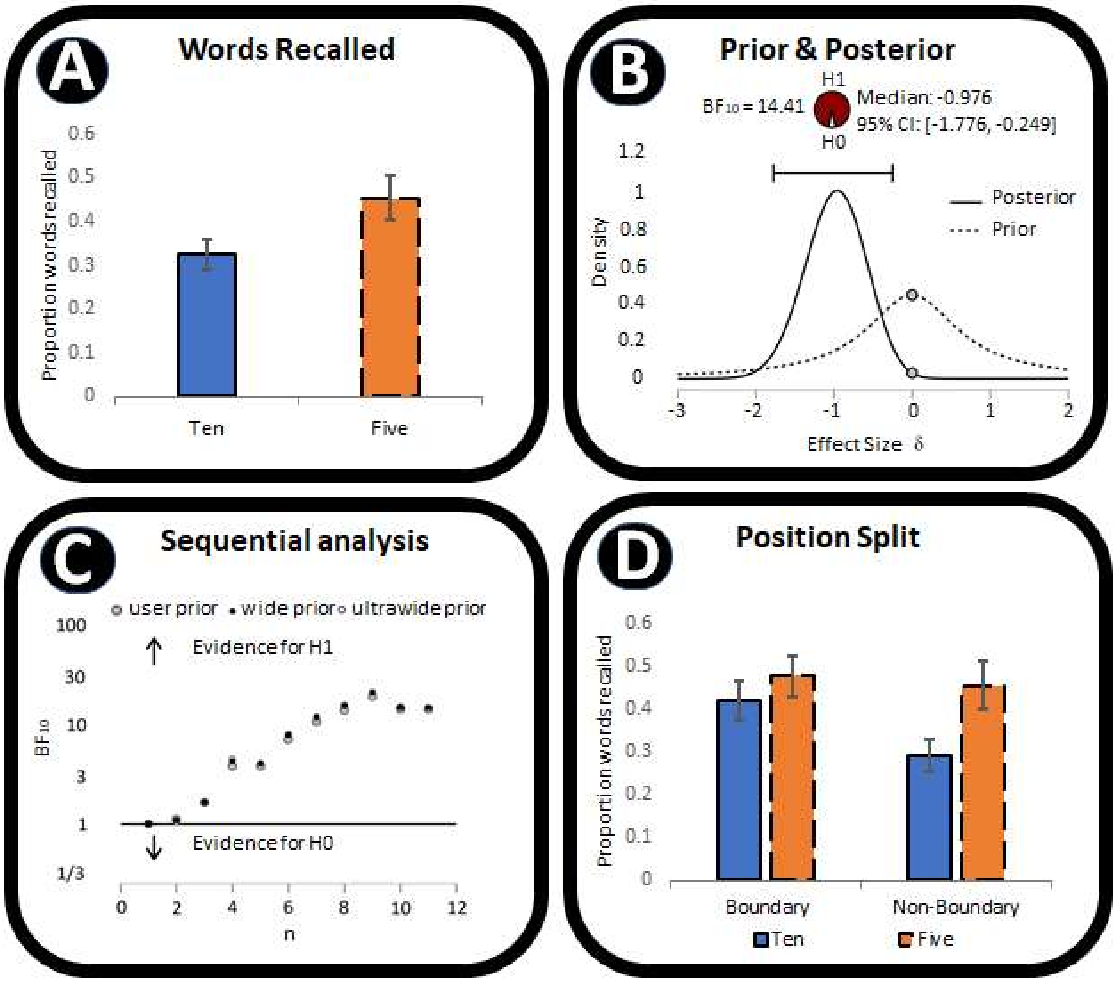

Figure 10, Panel A. Proportion of words recalled for Ten words (10 words per location across 4 locations) versus Five words (5 words per location across 8 locations) for Experiment 3. Panel B: Plot of prior and posterior. Panel C: Bayesian sequential analysis. Panel D: Memory improvement effect due to an increase in non-boundary words recalled.

Experiment 4 once again demonstrated a significant memory improvement effect when information is split into packets that may be maintained within working memory, in this case groups consisting of 5 words provided improvement over groups consisting of 10 words. The Bayesian sequential analysis displayed in Figure 10(C) indicated that 10 out of 11 participants provided evidence in favour of the alternative hypothesis: presenting segmented packets of information leads to significant memory improvement. Further analysis examined whether the improvement was due to boundary words (the first and fifth word presented at each location) or non-boundary words (the second, third and fourth words presented at each location). Figure 10(D) displays the recall performance for boundary and non-boundary words. These data were subjected to Bayesian repeated measures ANOVA with factors of packet size (segmented vs. non-segmented) and position (boundary vs. non-boundary). The Bayes Factor for segmentation was $BF_{incl} = 47.44$, indicating 'very strong' evidence for segmentation. The Bayes Factor for position was $BF_{incl} = 5.35$, indicating 'moderate' evidence in favour of position. The Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 3.96$, indicating 'moderate' evidence in favour of an interaction. As can be seen in Figure 10, when to-be-remembered information exceeded working memory capacity the improvement provided by segmentation was only present for words close to a boundary, while a distinct drop in performance is visible for non-boundary words.

Further analysis was conducted to determine the effect of presenting packets of words segmented in time. Adjusted Ratio Clustering (ARC) scores were calculated using every 5 words as a category for both the overcapacity (ARC = 0.25; SE = 0.1) and under capacity (ARC = 0.52; SE = 0.12) conditions. Analysis revealed 'moderate' evidence ($BF_{10} = 3.38$) in favour of an increase in clustering. The results are consistent with the differences in memory performance that our manipulation of working memory capacity produced, adding weight to the claim that segmentation effects vary with memory load.

Finally, Conditional Response Probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words.

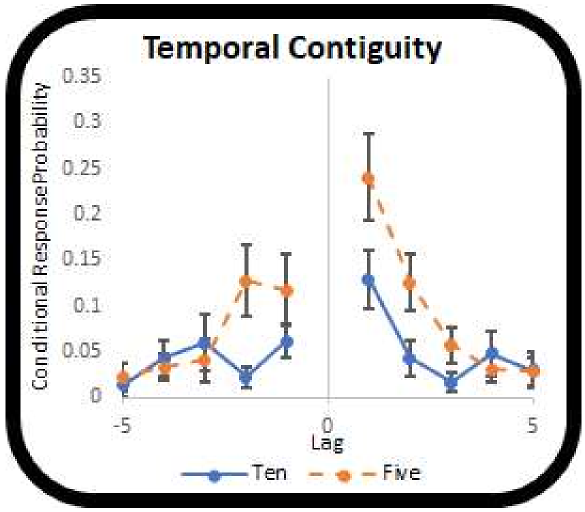

Fig 11: Conditional Response Probability (CRP) as a function of lag. Participants show anecdotal evidence for an increase in lag+1.

Analysis of CRP revealed that there was no significant difference in Lag+1 between the ten-word condition (M = 0.13; SD = 0.11) and the five-word condition (M = 0.24; SD = 0.16). As shown in Figure 11, with a Bayes factor $BF_{10} = 1.26$, the analysis provides 'anecdotal' evidence that presenting words in packets consisting of 5 words in comparison to packets consisting of 10 words, segmented by spatial-temporal gaps within a virtual environment does not result in an increase in recalling the words in the order of presentation.

Discussion

In Experiments 1-3, when to-be-remembered information could be comfortably held within working memory capacity, boundary position had no effect on performance. Consequently, in Experiment 4 we aimed to identify whether overloading working memory capacity (i.e., by increasing the number of words between boundaries) would reduce the benefits of segmentation, resulting in poorer performance for non-boundary (compared to boundary) words. As can be seen in Figure 10, and consistent with our hypothesis, the results revealed clear differences in memory performance, with a decline in the number of words recalled when working memory capacity was exceeded. The data also reveal a clear decrease in clustering, confirming that increasing the quantity of information between boundaries diminishes the effects of segmentation. Importantly, Bayesian analysis provided moderate support for the claim that the reduction in recall was largest for words furthest from the boundary, suggesting that words closest to the boundary had retained the benefits of segmentation.

The findings from Experiment 4 are consistent with Event Segmentation Theory, which predicts that if the number of words between boundaries overloads working memory then participants will be unable to remember the words furthest from the boundaries. From this perspective boundaries can be viewed as ‘anchor points’, such that to-be-remembered information encountered adjacent to boundaries will benefit from segmentation. Critically, the present findings suggest that the anchoring effects associated with segmentation are only visible once working memory capacity is exceeded - when the number of words to-be-remembered was well within working memory capacity both boundary and non-boundary words were equally well recalled. For Experiment 4 the analysis of temporal contiguity showed no significant increase in memory for temporal order even though the use of the same spatial-temporal gaps in Experiment 2 did show a significant increase. The presentation of 10-word groups may already be providing some benefit to memory for temporal order and presenting 5-word groups may not necessarily provide any further benefits.

Overall, therefore, the results of Experiment 4 suggest that memory can be optimised by presenting information in discrete segmented packets, if each packet can be maintained within working memory, with the boundaries defining the beginning and end of each event. In the general discussion we highlight the implications of the present findings for Event Segmentation Theory, as well as considering a number of alternative interpretations.

5.6 Interim General Discussion

Across four experiments we used a virtual learning environment to investigate the impact on free recall from episodic memory of spatial-temporal gaps and the presence of doorways during visual presentation of 40-word lists. The gaps and doorways were used in the virtual environment to create boundaries between subsets of words, and the experiments were set in the context of assessing predictions from Event Segmentation Theory (Zacks, 2020). Across Experiments 1, 2 and 3, we aimed to identify the essential features that define boundaries and act to segment events, each comprising subsets of the overall word list. To our surprise we found that while gaps generated by physical boundaries (movement through doorways) led to enhanced memory, consistent with Event Segmentation Theory, boundaries created solely by gaps in time were just as effective. Furthermore, and contrary to both Event Segmentation Theory (Zacks, 2020) and our expectations, all three experiments also revealed that the benefits of segmentation extended beyond the words presented immediately before or after a boundary. In Experiment 4 we investigated the limits of memory improvement that segmentation can provide, demonstrating that the benefits of segmentation are only tied to the boundary when to-be-remembered information exceeds working memory capacity. The results of Experiment 4 also demonstrated that maximum benefit for memory was obtained when the number of words within each segment was within the capacity of working memory.

Before considering implications for theory, we first briefly summarise the key results. Experiment 1 demonstrated a memory improvement effect along with increased clustering when boundaries were formed by spatial-temporal gaps and doorways. In Experiment 2 we removed physical boundaries, but the memory improvement and increase in clustering were still present, even though participants did not pass through a doorway between locations. Similarly, in Experiment 3 we employed boundaries defined solely by a temporal gap (without travelling through space or crossing physical boundaries) and found markedly similar improvements in recall and clustering to those reported in Experiments 1 and 2. Critically, because we used a virtual learning environment, we were able to ensure that the spatial and temporal boundaries were identical across experiments. Interestingly, in Experiments 2 and 3 participants showed an increase in recalling the words in the order of presentation. Serial ordered recall is not common in tests of episodic memory for very long lists, such as the 40-word lists used in our experiments. For example, Ward, Tan & Grenfell-Essam (2010), showed that for lists of 15 words, participants used free recall, even when they were instructed to use serial recall, and used serial recall for short lists, even when instructed to use free recall. In a similar fashion, when segmenting word groups that can be maintained within working memory with spatial-temporal gaps, it appears that participants were spontaneously recalling word groups in the order presented, even though the instructions were for free recall. Taken together, therefore, the present results demonstrate that the memory benefits associated with segmentation-based boundaries do not require either physical or spatial boundaries to be present - temporal boundaries alone are sufficient to enhance memory.

The experience of prediction errors driven by the presence of event boundaries is of central importance to Event Segmentation Theory. While previous studies of event segmentation have demonstrated the importance of prediction errors at moments of perceptual or conceptual shifts without the presence of spatial-temporal gaps (Swallow et al., 2009; Gold et al., 2017; Swallow et al., 2018) spatial-temporal gaps are also an effective means of imposing an event boundary. The present study challenges previous conclusions that prediction errors, driven by the presence of doorways, are the primary or only cause of the memory improvement effects seen in studies of event segmentation. For example, previous studies have demonstrated that spatial boundaries can act to impair memory performance; walking through doorways causes forgetting and spatial boundaries disrupt memory for temporal order (Radvansky, Krawietz & Tamplin, 2011; Horner, et al., 2016). Other studies have shown that travelling between real rooms during encoding can improve memory performance (Pettijohn et al., 2016; Smith, 1982, Smith & Rothkopf, 1984). Furthermore, Brunec et al., (2020) employed a series of turns along a route to establish boundaries and showed an increase in the subjective recollection of locations encountered prior to a turn. Previous research has also defined boundaries via shifts in context. For example, Clewett, DuBrow & Davachi (2019) demonstrated boundary-related memory effects associated with moving from a city street (surrounded by buildings) to a park area (surrounded by trees). Similarly, van Helvoort et al., (2020) presented paintings within a virtual museum, and showed that memory performance was dependent on the size of the spatial and temporal gaps between paintings during learning. The smaller the spatial-temporal gap the better the performance on successfully identifying adjacent paintings.

The present study also demonstrated memory improvements related to physical boundaries and to changes in spatial context. Importantly, however, the memory benefits remained when we removed these features, leaving boundaries between events that were defined solely by temporal gaps. In both the studies of employing boundaries consisting of turns (Brunec et al., 2020) or context-shifts (Clewett, DuBrow & Davachi, 2019), participants estimated a longer period of time passing when experiencing the boundaries. A range of studies has shown that our experience of time is influenced by the number of salient moments of change experienced, rather than solely due to the number of seconds passing (Clewett, Dubrow & Davachi, 2019; Brunec et al., 2020; Bangert et al., 2019). The presence of salient moments of change can, of course, be experienced as a temporal gap even if there is no difference in the amount of time passing. From this perspective, the segmentation of events may be a process that is dependent upon detecting moments of change; if no temporal gaps exist, they may be created by the detection of a salient physical change in the environment.

Event-Segmentation Theory is also challenged by a second feature of the current findings. Based on prior evidence (Kurby & Zacks, 2008; Swallow et al., 2009) and theoretical accounts (Zacks, 2020) we predicted that memory impairments should be greater for boundary than non-boundary words. Contrary to expectations, however, the benefits of segmentation found in Experiments 1-3 were present for both boundary and non-boundary words. Consequently, in Experiment 4 we manipulated the amount of information presented between boundaries, in order to ask whether the memory improvement effects are boundary-specific when to-be-remembered information exceeds working memory capacity. As predicted, when additional information had to be encoded the benefits of segmentation were clearly tied to the boundary, such that memory benefits were only present for words adjacent to a boundary. By demonstrating that memory improvement effects are larger for boundary than non-boundary words, the findings from Experiment 4 suggest a limit to the benefit that segmentation can provide. More importantly, taken together with the absence of boundary-specific effects in Experiments 1-3, and the fact that temporal gaps alone are sufficient to generate memory benefits, the present results show that physical boundaries (such as doorways) are not an essential feature of event boundaries.

As noted above, one potential interpretation of the segmentation effect is that the presence of physical boundaries and spatial-temporal gaps simply provide salient moments of change. While spatial-temporal gaps and context effects may serve as a basis for segmenting information, event boundaries can be more generally defined by any salient moment of change that increases uncertainty and lowers predictability. For example, Zacks et al., (2007; see also Zacks, 2020) proposed that a boundary is encountered whenever a prediction error occurs. According to this view participants have an expectation about what is going to happen next, but when what happens next is unexpected a boundary is experienced, which packets the continuous flow of information. From this perspective spatial-temporal gaps act as a trigger to encode recently encountered information, such that all of the information currently maintained in working memory is encoded as a single episode into long-term memory (freeing working memory for the next packet of to-be-remembered information). This view receives support from neuroimaging data that suggest recently encountered information is rapidly ‘replayed’ when an event boundary is encountered (see Silva, Baldassano & Fuentemilla, 2019). Similarly, Ben-Yakov & Henson (2018) provided evidence that activity within the hippocampus (a core part of the brain systems supporting episodic memory) is sensitive to boundary points when participants watch films. Clearly, then, the saliency of boundaries is important for the subsequent influence that boundaries have on memory. In the present experiments, therefore, the effect of segmentation likely results from the saliency of the moments of change between word packets, rather than being specifically due to changes in space and time.

The current findings also rule out one specific form of salience, known as the Von Restorff effect (Von Restorff, 1933; see also Hunt, 1995). Von Restorff presented a list of words including a single number and showed that memory for the number was improved as it stood out relative to the words it was presented with. Importantly, however, the Von Restorff effect produces no improvement for the words on either side of the presented number. In practice, of course, participants in experiments may identify any salient moment as a boundary, and segmentation-related improvements in memory performance may sometimes depend on Von-Restorff effects, rather than boundaries that act as triggers to encode all recently encountered information. For example, when participants are asked to segment films (e.g., see Newtson, 1973; Zacks, Speer, Reynolds & Abrams, 2009) the boundary points likely align with salient points that are intentionally created by the film makers. By contrast, in the present study, if the memory improvement effect was due to an increase in salience for the words presented closest to boundaries, then the increase in recall performance should have been entirely due to an increase in the number of boundary words recalled. However, when the number of words between boundaries could be maintained within working memory there was an increase for every word between boundaries. Given the foregoing considerations, our view is that the memory benefits seen here are not due simply to salience (in the Von Restorff sense).

We now turn to a potential alternative interpretation of our findings - namely that the benefits to memory reflect the role of temporal grouping within working memory. As noted above, our data strongly suggest that the benefits of segmentation can be achieved via the introduction of temporal gaps. In Experiments 1-3, when the amount of information to-be-remembered was within working memory capacity, recalled words also exhibited an increase in clustering (following segmentation, compared to no segmentation). Similar temporal grouping effects have been demonstrated previously using short word lists within working memory (Hitch, Burgess, Towse & Culpin, 1996) and the benefits of temporal gaps for learning are well established within the wider working memory literature (e.g., see Farrell, 2012). From this perspective the present studies can be viewed as providing evidence of similar temporal clustering, but for much longer lists of words, raising the possibility that increases in recall performance may also have been due to the temporal clustering mechanism that has been demonstrated within working memory. Information that is temporally synchronous within working memory prior to experiencing the boundary may become bound into a single event simply by being active within the same time window. Similarly, Kahana, (1996) demonstrated an improved memory performance for information that is experienced close in time. One interpretation of the temporal clustering effect is that items appearing close in time share a greater contextual overlap. By contrast, items appearing further apart in time are separated due to a decreased contextual overlap (Howard & Kahana, 2002). Evidence in support of this view can be found in Hartley, Hurlstone & Hitch (2016), who examined the effect of rhythm on memory in a direct comparison of irregular word groups separated by temporal gaps. Participants were either informed or uninformed as to the grouping patterns with which they would be presented. There was no effect of predictability on subsequent memory performance. Importantly, while there were effects on recall performance between different grouping patterns, the predictability of the grouping pattern made no difference. The benefits found when employing predictable groups of 3 words is also consistent with the proposal that the number of items between boundaries has an important influence on subsequent memory performance. In addition, the null effect of predictability in these studies is consistent with the proposal that the presence of grouping effects is primarily due to perceptual processes, which could be governed by the gestalt laws of perceptual organisation. Overall, therefore, the present findings provide support for the theory that the experience of temporal gaps is an important component for generating segmented sequences of events in memory. It is, perhaps, also worth highlighting that although event segmentation and temporal clustering accounts are not necessarily mutually exclusive, to date we are not aware of any studies designed to discriminate between these views.

One obvious attraction of the temporal clustering view is that it readily explains why boundary position effects were found in Experiment 4, where recalled words showed a decrease in clustering when working memory capacity was exceeded during encoding. The differences in memory performance shown in Experiment 4 were only visible because we compared performance above and below working memory capacity. Our data therefore explains why previous studies have failed to find evidence that segmentation leads to increases in clustering. For example, Pettijohn et al., (2016) found no differences in clustering when lists of words were presented in either a single set of 40 or segmented into four sublists of 10 (each of which exceed working memory capacity). By extension, the fact that increases in clustering may require a comparison that straddles working memory capacity suggests that there may be a “Goldilocks’ zone” in which the benefits of segmentation are maximised. Previous work has proposed that the segmentation of events occurs within working memory (Richmond, Gold & Zacks, 2017; Radvansky, 2017) and the current findings reinforce this view. Crucially, however, the current findings also highlight that temporal clustering provides another plausible account of the memory benefits. Future research is required to systematically manipulate clustering in space and time, to reveal whether temporal clustering can account for memory improvements.

Finally, the present findings also demonstrate that virtual learning environments can use spatial, temporal and physical boundaries to improve the quantity of information that is available for episodic recall. In this regard our findings receive support from real world studies examining strategic approaches to enhancing memory using the Method of Loci, in which each location provides a start and end boundary for a mental image. In previous studies of mnemonic training, recall performance and memory for serial order typically has been dependent on the use of a mnemonic technique. Improvements were not present if participants only conducted additional rehearsal of the presented words. For example, in a study of mnemonic training one group of participants were specifically instructed to conduct additional rehearsal after receiving every fourth word (Roediger, 1980). The rehearsal group showed no benefits, whereas the groups that were provided with mnemonic training such as the Method of Loci showed an increase in words recalled and an improved memory for serial order. Similarly, a study by Bouffard et al., (2017) compared different mnemonic techniques including Method of Loci training, the use of temporal mnemonics with an autobiographical mental timeline and the use of the steps to making a sandwich. All three mnemonics showed increases in number of words recalled and memory for serial order in comparison to uninstructed free recall, for which participants self-reported the use of rehearsal. The increases in recall performance and serial order were only present in the groups that received mnemonic training, and furthermore, carrying out the memory test a second time did not produce a practice effect or memory benefits when only rehearsal was employed. Training in the use of time alone or the procedural steps to making a sandwich provided similar benefits to training in spatial mnemonic strategies. While spatial-temporal gaps can produce performance benefits, memory improvement effects can be found without employing training based on spatio-temporal strategies.

The present research employs a reductionist approach. After finding an effect, components of the experiment were systematically removed. If the effect changes or disappears then we could conclude that the removed component had an important influence on the effect. Using this approach, the present work provides new evidence to show that external cues such as moving between locations in a virtual environment or imposing temporal gaps between packets of information can be employed to segment events, increase clustering, increase temporal contiguity and improve the amount of information that is available for episodic recall. The data also suggest, however, that whilst temporal boundaries are sufficient to produce memory benefits, introducing temporal gaps via the imposition of spatial or physical boundaries may be more effective (noticeable, engaging or salient, etc.) within a virtual environment. It is also important to recognise that event segmentation has been proposed as a working memory process that supports the transfer of information from working memory to long-term memory (Richmond, Gold & Zacks, 2017; Radvansky, 2017). Working memory has been defined as having a capacity of 3-5 chunks (Cowan, 2010) and the Event Indexing Model proposes that a boundary could be defined as a change in any one of 5 dimensions; time, space, entity, goal & causality (Zwaan, Langston & Graesser, 1995). The results of the present study therefore suggest a possible approach to improving episodic memory by tailoring to suit the constraints of working memory, segmenting to-be remembered items with spatial-temporal gaps; Indeed, our findings demonstrate that simply presenting segmented packets of information can provide memory benefits and could be the basis of providing more efficient and engaging learning content. Moreover, from a methodological perspective, using game development software to create virtual environments offers greater control over the segmentation of stimuli (along with precise information about any behavioural responses) than studies with real environments or movies can provide.

Although additional rehearsal time has been shown to provide no benefit to long-term learning, there remain potential limitations in the present study. The segmented conditions were always presented second, to minimise the potential use of a segmentation strategy in the non-segmented condition. Future work could examine whether the effects found in the present study will persist if the segmented conditions are presented first, or if the presence or absence of segmentation is a between participant variable. Likewise, future studies could explore the potential benefits of providing segmentation training (Flores et al., 2017) similar to the studies of mnemonic training (Roediger, 1980; Bouffard., 2017). Furthermore, a previous study by Bhatarah et al., (2009) presented eight-words to participants and found differences in recall performance between slow and fast presentation rates for both free recall and immediate serial recall. Future studies should ask the question what is required to distinguish between the encoding of a single event consisting of eight words as opposed to eight events each composed of a single word. The current findings also leave open the possibility that there may be a ratio of presentation rate within an event, to the size of temporal gap between events, which is necessary to find an effect. The ratio may also depend on individual differences in segmentation ability and in working memory capacity, with some participants able to efficiently segment information with moments of low salience and/or show benefits with more items per segment. Future work based on the present study could continue to employ a reductionist approach to determine the effects of presentation rates and the salience of the moments of change between stimuli in providing structure to memory.

In conclusion, across a series of experiments we identified the importance of temporal gaps for providing structure to memory and increasing the amount of information that can be remembered. The optimisation of episodic encoding may involve filling up working memory with material linked to each group of stimuli. Encountering a salient moment of change imposes an event boundary, triggering episodic encoding, and clearing the contents of working memory so that new information can be taken in. The previous packets are then stored in long term memory, and residual traces in working memory of the most recent packet are removed or overwritten by new packets. Based on the analysis of temporal contiguity, the Event Indexing Model (Zwaan, Langston & Graesser, 1995) and the wider literature identifying segmentation at perceptual and conceptual shifts (Swallow et al., 2009; Gold et al., 2017; Swallow et al., 2018), we conclude that prediction errors proposed by Event Segmentation Theory, driven by the presence of doorways, may have a specific effect of disrupting memory for temporal order. While the memory improvement effect from segmentation, the increase in clustering, and the improvement in memory for temporal order may be driven by predictable rhythms of temporal gaps, temporal gaps may exist on a continuum of salient moments of change (including the dimensions highlighted in the Event Indexing Model). We predict that the effects found in the present study may also be present in event sequences segmented by perceptual and conceptual shifts, rather than being unique to spatial-temporal gaps. Finally, we also note that previous studies have identified a hierarchical event structure with segmentation occurring at both a fine and coarse grain (Kurby & Zacks, 2008). Future studies will be required to clarify whether the hierarchical event structure could also be described as nested event sequences, with fine-grained segmentation driven by predictable perceptual moments of change.

The present experiments therefore propose a structure for learning, involving salient moments of change that can be defined by boundaries, acting as anchors around which the episodes form. From this perspective episodic memory is formed from sequences of events, with salient moments of change acting as boundaries to define the beginnings and ends of each event. The present findings suggest that episodic encoding can be optimised by imposing spatial-temporal gaps around packets of information as they are maintained within working memory. The current study also suggests that use of event segmentation within virtual environments is a fruitful approach to understanding the interactions between working memory and episodic memory. Further questions remain as to the contributions to the structure of memory that predictable perceptual moments of change, prediction errors and an ongoing process of temporal context drift may provide. Most importantly, the present findings demonstrate that employing predictable spatial-temporal gaps to segment word groups that can be maintained within working memory provides an effective means of optimising memory performance – even without the presence of doorways.

Chapter 6: Identifying a 'goldilocks zone' for episodic encoding. Experiments 5-10.

6.1 Introduction

Working memory involves the temporary storage of information (Baddeley & Hitch, 1974; Baddeley & R. Logie, 1999; Baddeley 2010) whereas episodic memory involves the long-term storage of one's life experiences (Tulving, 1972, 2002; Burgess, Maguire & O'Keefe, 2002). Much is known about how these different memory systems operate, for example that working memory has short-term, limited capacity (Miller, 1956; Cowan, 2010; R. Logie, 2011) and may generate novel representations of events (Hassabis & Maguire, 2007; 2009), whereas episodic memory stores longer lasting event sequences (Mahr & Csibra, 2018; Buzsáki & Tingley, 2018). Considerable uncertainty remains, however, about the relationship between these memory systems, as not all the information represented in working memory is successfully transferred to episodic memory. In broad terms, therefore, the aim of the current study is to investigate why information in working memory sometimes is, and sometimes is not encoded into episodic memory. More specifically, we are asking whether it is possible to optimise the transfer of information from short-term to long-term memory. One approach to this issue is to focus on the learner. For example, researchers have highlighted how working memory may be trained to improve capacity (Norris, Hall & Gathercole, 2019; Norris, Holmes & Gathercole, 2019; Green & Newcombe, 2020). From this perspective, it is argued that long-term learning can be optimised by developing skills that reduce the load on working memory capacity. However, here we take an alternative approach that involves manipulating the way in which information is presented to learners.

As we outline below, across a series of four experiments we ask whether to-be-remembered information can be organised to make better use of existing working memory capacity. As well as offering an alternative route to supporting memory, our approach examines the role that event-boundaries play in mediating the relationship between working memory and episodic memory. Previous work has also identified that the boundaries between events (e.g., gaps in space or time) can provide structure that supports the successful transfer of information from working memory into long term episodic memory (See chapter 5) (M. Logie & Donaldson, 2021). Critically, building on prior findings, here we examine whether the amount of information between event boundaries can be manipulated in a way that enhances memory without requiring the development of additional working memory capability. In memory theory terms, therefore, our aim is to discover whether there is a 'goldilocks zone' – whereby the presentation of material is 'just right' for ensuring information can be remembered.

The functional organisation of working memory and its interactions with episodic memory are the subject of long running debate (e.g., Atkinson & Shiffrin, 1968; Baddeley, 1986; Baddeley & R. Logie, 1999; Barrouillet & Camos, 2015; Broadbent, 1958; Cowan, 1999; for recent reviews see Forsberg, Adams & Cowan, 2021; R. Logie, Camos & Cowan, 2021). However, for the purposes of the experiments presented here, we only make the broad, and generally agreed assumption that working memory is a limited capacity temporary memory system. Our hypotheses are neutral with respect to the range of theories of working memory, with one notable exception. An initial concept of working memory, represented in the model by Atkinson and Shiffrin (1968), explicitly characterised working memory as a temporary short-term store responsible for maintaining and manipulating incoming sensory information. However, if working memory was no more than a gateway to long-term memory, then the contents of working memory would consist of raw sensory images. It is clear that the contents of working memory comprise, for example letters and words that rely on reading and language knowledge, or objects and object shapes that might or might not have been encountered previously. Therefore, we assume that, to make sense of the world within working memory, sensory input must first activate knowledge about that input in long-term memory, and the activated knowledge then becomes available to working memory (R. Logie, 1995; 2011; 2021). This view is also consistent with the theories of working memory proposed by Baddeley (1986; Baddeley, Hitch, & Allen, 2021), and Cowan (1999; Cowan, Morey, & Naveh-Benjamin, 2021). The issue for the experiments that we report here is how the limited information in working memory result in an episodic record in long-term memory.

A traditional approach to studying the nature of interactions between working memory and long-term memory is to employ Hebbian repetition learning (Hebb, 1961). The original approach involved participants performing immediate serial recall on successive sequences of nine digits, with the same sequence of nine digits presented on every third trial. Participants show a gradual learning of the repeated sequence over multiple repetitions. Learning is not dependent on awareness of the repetition. One interpretation of the Hebb effect is that repeatedly maintaining information within a short-term store leads to gradual long-term learning (Atkinson & Shiffrin, 1968). This would also be the interpretation of the view that working memory comprises activated long-term memory. However, further studies failed to find evidence for the interpretation that simply holding, or rehearsing information within short-term stores results in long-term learning (Craik & Watkins, 1973). Later work found that Hebbian learning may depend on domain-specific resources for verbal (Baddeley, Gathercole & Papagno, 1998) or visuospatial information (Sukegawa, Ueda & Saito, 2019). Previous studies have shown that information held within working memory may be rapidly lost without being encoded into long-term memory.

In a series of experiments employing Hebb repetition learning and change detection (R. Logie, Brockmole & Vandenbroucke, 2009) participants showed no learning even after 60 repetitions of the same array of colour, shape and location combinations. In a later study Shimi & R. Logie (2019) employed a similar learning paradigm in which the same array containing several coloured shapes was presented to participants over 120 trials. On half of the trials, the test array was identical to the memory array, whereas on the other half of trials, the test array contained a change where either two colours swapped positions, or two shapes swapped positions with every other colour-shape location remaining the same. Participants were also required to conduct articulatory suppression to prevent the use of phonological codes for the visual-spatial stimuli. Some learning was observed, but this was very slow, and performance did not reach ceiling, even after 120 repetitions. The authors proposed that during any given trial, a representation of the array is maintained within a temporary, domain-specific short-term visual cache, the contents of which are over-written by the study array on the following trial, even if that array is identical. Repetition was thought to lead to the slow build-up of a weak episodic trace that contributes to long term learning and eventually allows participants to detect the change between study and test arrays on change trials. So, during early trials, when no learning could have occurred, performance was assumed to be supported by the visual cache, but as the number of repetitions increased, performance was assumed to rely on a gradually strengthening trace in episodic memory. This conclusion gains support from an earlier study by Colzato *et al*. (2006) who showed that participants could recall details of a presented array after completion of the experiment, although learning of the array did not benefit performance across experimental trials. The conclusion is also supported by a later study that demonstrated that long-term memory is required for identifying whether the currently presented array of colours and shapes is different from a previously presented array (Goecke & Oberauer, 2021).

In the study by Shimi & R. Logie (2019) it is notable that participants showed rapid learning of the repeated array when awareness of that repetition enhanced their ability to detect a salient moment of change that occurred on half of the trials. An alternative account to Hebbian learning is that learning is dependent on prediction errors triggering a memory update (McClelland, 1994; Radvansky & Zacks, 2014; Richmond, Gold & Zacks, 2017). That is, if the next event is not expected by the participant, it is more likely to result in episodic encoding. Because the study array was repeated in the Shimi and R. Logie study, as participants became aware of the repetition, they would increasingly predict that the next array that they see, including the test array, would be the same. When a change occurs in the array, this would result in a prediction error, leading to greater strengthening of the episodic trace for the array. Participants who did not become aware of the repetition would be less likely to predict a repeated array, and so an array showing a change would not be a particularly salient event. However, as a further alternative to prediction errors, episodic encoding may be triggered by the detection of a moment of change as and when the moment occurs.

The benefits for immediate recall when employing temporal groupings within short lists is well established (Hitch, 1996; Burgess & Hitch, 2006; Hartley, Hurlstone & Hitch, 2016). However, in later work on long-term learning, M. Logie and Donaldson (2021) (see Chapter 5) explored the impact on episodic memory of moments of change by presenting participants with much longer 40-word lists for delayed free recall. This offered the possibility of also exploring temporal order, which was not addressed in the Shimi and R. Logie (2019; see also Forsberg *et al*., 2021) studies. Words were presented visually across multiple rooms in a virtual environment, and the number of words in each room was varied across experimental conditions. When five words were presented in each room across eight rooms, participants recalled more words in a final test of free recall than when ten words were presented across four rooms. It was argued that moving between rooms in the virtual environment provided salient moments of change, and that these moments of change defined event boundaries that acted as triggers for episodic encoding of the information that was being held within working memory.

Previous accounts propose that the transfer of information from working memory into long term memory may depend on repetition with Hebbian learning or in terms of prediction error gating (McClelland, 1994; Radvansky & Zacks, 2017; Zacks, 2020). Moment to moment, predictions are created and when encountered information does not match the predictions an error is experienced, which packets incoming information and may act as a trigger for encoding recently encountered information maintained within working memory into long-term storage. Segmentation with prediction errors has been shown to influence the structure of long-term memory, with an improved memory for information encountered close to event boundaries defined by prediction errors (Swallow, Zacks & Abrams, 2009). In addition to prediction errors, based on previous work (M. Logie & Donaldson, 2021), segmentation may depend on salient moments of change rather than prediction errors, information held within working memory may be quickly erased if no moments of change are encountered. Experiencing event boundaries defined by spatial-temporal gaps when travelling between rooms within a virtual environment may act as a trigger for encoding information from working memory into longer-term storage. Since working memory capacity is limited, if the amount of information exceeds that capacity before a moment of change is detected, the information may be poorly encoded in episodic memory.

In a previous study (M.Logie & Donaldson, 2021) (see Chapter 5) word lists consisting of a total of 40 words were segmented within a series of virtual rooms without prediction errors driven by the presence of doorways. When five words were presented between room changes, there were no differences in memory performance for boundary and non-boundary words, leading to good final free recall performance. However, with packets of ten words, the capacity of working memory was greatly exceeded before the room change occurred, leading to poorer subsequent free recall from the full word list. When presenting 10 words per segment the words close to the event boundaries (the first and last words in each segment) tended to be remembered better than words in the middle of each segment. These serial position curves appeared in each segment of words, not just for the first few or last few of the 40-item list. Differences in boundary and non-boundary items may depend on the quantity of information encountered between boundaries and may be governed by previously established capacity of working memory. This supported the argument that the episodic memory representation of the list was punctuated by the shifts between virtual rooms, without prediction errors driven by passing through doorways, acting as event boundaries between each word segment. Previous work has found differences in boundary and non-boundary words for 10-word packets. Consequently, in the current study we ask whether differences in memory for boundary and non-boundary items may depend on a working memory capacity limit for the number of items presented between boundaries.

In a related study, Forsberg, Guitard & Cowan, (2021) presented arrays of various set sizes (2, 4, 6 or 8) of black line drawings of nameable everyday objects. During a trial, participants were presented with an array of either 2, 4, 6 or 8 items, and after a short delay, participants were presented with a single item along with 6 options to select the level of confidence on whether the displayed item was presented in the recent array. At the end of the test phase participants were presented with single items and again asked to select from 6 options to select the level of confidence on whether the displayed item was present in any of the previously studied arrays. The results showed a graded benefit with a higher proportion of correct responses on the long-term memory task for 2 item sets than 8 item sets. The authors concluded that the results outline the presence of a working memory bottleneck for long term learning. Episodic encoding will depend on the size of the presented array relative to working memory capacity. Unlike in previous studies (e.g., Shimi & R. Logie, 2019), the use of nameable images without articulatory suppression allowed for the use of both phonological and visual-spatial codes to maintain mnemonic representations, allowing for more efficient long-term learning (Mayer, 2002).

One limitation of the M. Logie and Donaldson (2021) study was the use of lists of highly imageable words, and similarly, Forsberg and colleagues used line drawings of highly familiar objects. It is well established that imageable words and pictures of objects can allow for the availability of mental images, as well as lexical and semantic codes (e.g., Paivio, 1971). It is possible that the advantage found by Forsberg *et al.* for small packets of objects and for five-word packets in the M. Logie and Donaldson study allowed participants to generate meaningful mnemonic representations among the presented items, but that this was more difficult to do with larger packets of pictures in the former study, and of words in the latter study. This offers an alternative interpretation, for the memory advantage found with smaller packets of items.

The experiments reported here followed the same general procedure as M. Logie and Donaldson (2021), using movements between locations within a virtual environment as highly salient moments of change to act as triggers for episodic encoding of word packets shown in each location. The primary aim of the following experiments was to delineate a potential 'goldilocks zone' for optimising long-term learning based on the segmentation of working memory packets without the need for repetition. Long-term memory performance should improve when the quantity of information between boundaries is reduced, such that the information can be maintained within working memory. Working memory capacity has previously been reported as having a hard domain-general limit based on a number of slots (Miller, 1956; Luck & Vogel, 1997; Cowan, 2010) whereas alternative accounts suggest that capacity limits may depend on multiple domain-specific capacities, for phonological and visuo-spatial information, that may work in concert to support performance (Baddeley, 1974; Baddeley & Hitch, 1984; Logie, 2011). Capacity could also be temporally limited, in that information held within working memory has been argued to decay over time regardless of the domain, and capacity is dependent on aspects such as speed of articulation (Towse & Hitch, 1995; Barrouillet & Camos, 2015). Furthermore, rather than a hard limit based on number of slots there may be an unreliable limit with an increasing probability of losing items as list lengths increase (Newell, 1972; Bays, 2015). Rather than distinguishing between alternative accounts it may also be possible that all accounts are correct and findings in support of any one view will depend upon how memory is tested (Alvarez & Cavanagh, 2004; Anderson *et al*., 2011).

The primary aim of the current study is to determine to what extent episodic encoding can be optimised by manipulating the quantity and domain of information between event boundaries. Would overloading working memory with too many words between boundaries impair long-term memory performance? A secondary aim was to contribute to work in identifying the nature of working memory capacity limits: Is there a hard domain-general slot limit for working memory capacity? And to what extent does long-term learning depend on representations constructed within working memory that is distinct from episodic memory? Finally, our aim was to replicate and extend our previous work using low imageability words that would be less likely to result in the generation of visuo-spatial imagery or semantic associations within each word segment. Would under-loading working memory by limiting the availability of visual-spatial information between boundaries also impair long-term memory performance?

The virtual environment used in the current set of experiments was created in Unity 3D (https://unity3d.com), as illustrated in Figure 12. The environment is modular in design and allows participants to be guided through a series of rooms, within which a set of stimuli can be presented for learning. Importantly, the features of the environment can be controlled and manipulated, including the to-be remembered information within an event and the event boundaries employed to segment events. The first three experiments make use of the virtual environment to manipulate the number of highly imageable words presented between boundaries while maintaining the same total number of words. The final experiment makes use of the same virtual environment to present words of low imageability, to identify whether benefits of segmentation may be found when limiting the availability of visuospatial codes.

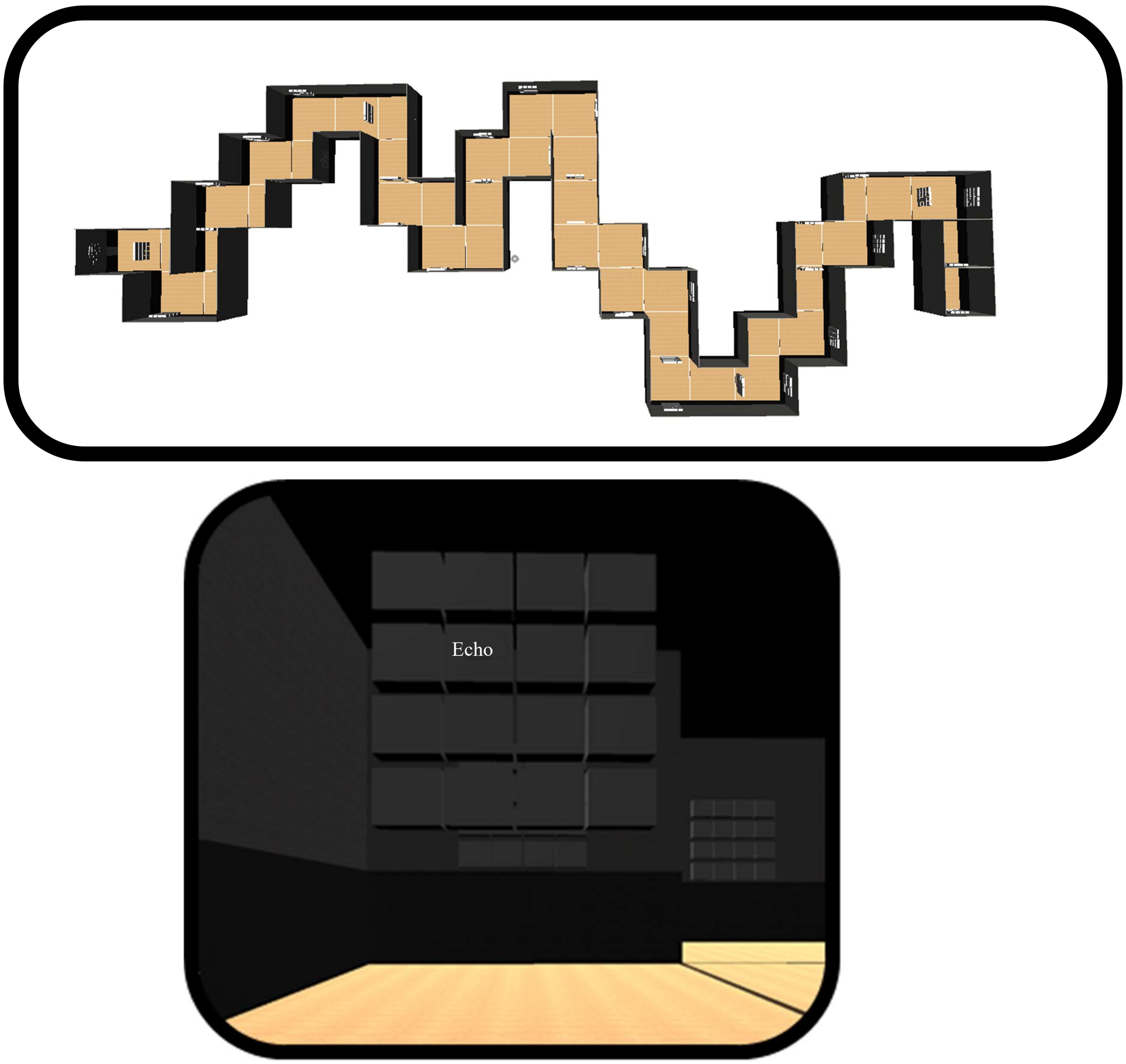

Figure 12: Top Panel, view of the virtual learning environment created in Unity3D. Every room is identical in size, shape, and colour. Movement through the space was automatic, ensuring consistent visual input, with a consistent pace, for all participants. Experiments 5, 6, 7 & 10 employed a subset of displayed rooms; Experiment 8 & 9 employed every room. Bottom Panel, first person view within a room displaying a word of low imageability used in Experiment 3. The virtual environment allowed experimental control over the number of rooms and the number of words presented within each room. Within each location the words appeared sequentially, in a random order and at random locations on the grid.

6.2 Experiment 5

The aim of Experiment 5 was to build on previous work that found an increase in the proportion of words recalled when segmenting a forty-word list into groups of ten (Smith, 1982, 1984; Pettijohn *et al.*, 2016). An additional aim of Experiment 5 was to further investigate the result of Experiment 4, examining whether the benefits of segmentation may be governed by working memory capacity, which for the present paradigm may be defined as three-five (Cowan, 2010) or seven plus or minus two (Miller 1956). The benefits of segmentation may be dependent on the quantity of information presented between boundaries lining up with working memory capacity. If so, there should be an absence of memory benefits when comparing a condition providing no segmentation to a condition that segments packet that each exceed working memory capacity. Consequently, Experiment 5 examined memory performance when comparing the presentation of a continuous list of forty-words to a segmented condition consisting of four packets of ten words. Segmentation was provided by salient moments of change, provided by moving between locations in a virtual environment, without the presence of doorways. The virtual environment is shown in Figure 12. Each room was a neutral grey, all rooms were the same size and shape, and participants were automatically moved between locations. Automatic movement was employed to ensure that every participant experienced the same spatial-temporal gap between rooms, without depending on participants' ability to navigate within a virtual environment. While experiments involving Hebbian learning traditionally involve multiple repetitions and tests of detecting subtle moments of change, the focus of Experiment 5 was to identify a potential upper limit for the beneficial memory effects of presenting segmented packets that may be maintained within working memory. The current study employs the sequential presentation of words rather than static visuo-spatial arrays to enable the use of free recall and analysis of clustering and temporal contiguity.

Previous studies have identified memory benefits to long-term learning when presenting segmented event sequences within a virtual learning environment (M. Logie & Donaldson, 2021). The current study employs the same virtual learning environment and builds on previous work to further explore the proposal of a goldilocks zone for episodic encoding. The main aim of Experiment 5 was to identify whether memory performance would improve as a result of segmentation if the information presented between boundaries, defined by moments of change, exceeded a previously reported upper limit of working memory capacity. Any benefits should be visible in terms of number of words recalled, clustering and temporal contiguity. If working memory is limited to seven plus or minus two items, then we would expect limited or no benefit when comparing a list with no imposed moments of change and lists that contain moments of change but exceed the seven plus two upper item limit of working memory between boundaries. Consequently, in Experiment 5 memory performance was examined when comparing a condition consisting of forty words presented within one location to a condition consisting of ten words presented per location split across a total of four locations.

Methods

Participants

A total of 11 participants, with age range 18-39 years (M = 21.2; SD = 6) were recruited through the University of Stirling online recruitment portal, and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling General University Ethics Panel.

Materials

The experiment made use of the same virtual learning environment reported in (M. Logie & Donaldson, 2021). The environment was created with Unity (https://unity3d.com) and allows for the presentation of segmented event sequences across a series of virtual locations.
The environment consisted of a series of identical rooms, each with a single door to the next room that was either on the left, the right or straight ahead. Each room had a 4 by 4 grid directly ahead of the entrance to the room, where words appeared in random locations (cf. Figure 12 Panel B). The experiment involved presenting a series of highly imageable words on the grid. Words of high imageability were used because they ensure good levels of remembering (compared to words with low imageability; see Paivio, 1971; Reder *et al*., 2006; Reder, Park & Kieffaber, 2009). Presenting a highly imageable word at a location on the grid was used to provide a mnemonic representation of an item to be maintained within working memory. The words used in the experiment were taken from the MRC Psycholinguistic database (Coltheart, 1981), and every word had a minimum imageability rating of one standard deviation above the mean. The current study employed the same 80 words used in (M. Logie & Donaldson, 2021). For the non-segmented condition forty words

were selected at random and presented in a random order, and the remaining forty were presented in a random order for the segmented condition.

Procedure

Study phase

The experiment consisted of 2 sets of a study phase followed by a test phase. During the study phases participants were presented with lists of words in virtual locations. For the study phase containing no moments of change (non-segmented condition), forty words were presented at random locations on a 4 by 4 grid within a single location. For the condition containing moments of change (segmented condition), ten words were presented at random locations on a 4 by 4 grid before participants were automatically moved to the next location for the next ten words, across a total of four locations. In both conditions, words were separated with a gap of 1 second and were present for 3 seconds. After all words had been presented at one location there was a 3 second pause, moving to the next location would take 6 seconds followed by another 3 second pause before the next word appeared. After each study phase, participants were asked to engage in a backwards counting task for 2 minutes before being asked to recall as many words as possible.

Movement through the environment was automatic so that every participant experienced the same gap in space and time between rooms. The automatic movement also controlled for the ability to navigate in a virtual environment. After the study phase there was a two-minute gap before the test phase, during which participants were asked to count backwards, ensuring that the last words presented were no longer being held in working memory.

Test phase

Following the 2-minute break after the study phase, participants were again automatically moved to the next location where instructions were presented for the test phase. During the test phase, participants were asked to type the remembered words, one at a time, into a text box that appeared in the centre of the screen. Participants were free to recall the words in any order and were asked to inform the experimenter when they could not recall any more words. Both the words presented during the study phase and the words typed in the test phase were automatically recorded and stored in a text file to allow for subsequent analysis. After the first test phase the experimenter pressed a button to load the next condition, brief instructions were provided to participants, that they would again be presented with a series of words within the virtual environment and asked to remember as many words as possible.

Statistical Analysis

The analysis employed Bayesian methods, carried out with JASP (JASP Version 0.12). Bayesian paired sample t-tests were used to determine whether the strength of evidence was in favour of the alternative or null hypothesis. A Bayes Factor (BF) of between 3 and 10 is taken as 'moderate' evidence for the alternative hypothesis, whereas a BF between .33 and .1 provides 'moderate' evidence in favour of the null hypothesis. Furthermore, the Bayes factor has the same meaning regardless of number of participants, unlike p-values (e.g., see Jarosz & Wiley, 2014; Wagenmakers, 2007; Wagenmakers *et al*., 2016; Wagenmakers *et al*., 2018 for a complete classification of Bayes factor scores). Adjusted Ratio Clustering (ARC) scores were also calculated using the category clustering calculator for free recall (Senkova & Otani, 2012; Pettijohn *et al*., 2016). ARC scores provide a measure of how recalled words are clustered by the packets that the words were presented in. The ARC scores are adjusted for the expected chance level. Analysis of Conditional Response Probability (CRP) as a function of lag was conducted to determine effects of temporal contiguity (Kahana, 1996; Healey, Long & Kahana, 2019). A significant increase in lag+1 represents an increase in the probability that a participant will recall the next item from a forward adjacent position.

Results

The results are summarised in Figure 13, suggesting that providing packets containing ten words does not provide a memory improvement. Findings are described below in relation to the individual panels shown in Figure 13.

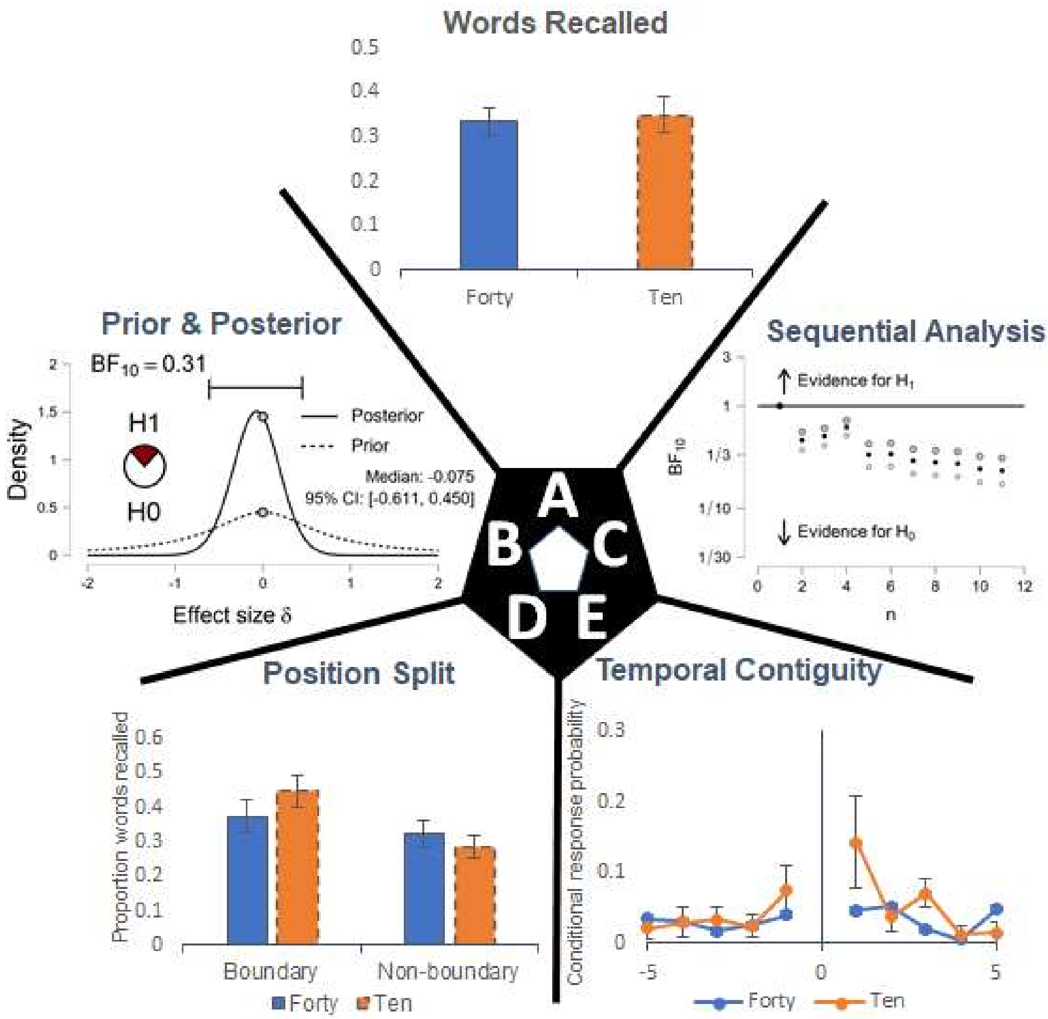

Figure 13, Panel A: Proportion of words recalled for 40 words presented in 1 location versus 10 words per location across 4 locations) showing no increase in words recalled. Error bars represent ± 1 standard error of the mean. Panel B: Bayesian paired sample t-test, displaying 'strong' evidence that segmentation led to improved long-term learning (BF_{10}). The density function illustrates the difference in effect size between prior and posterior estimates, and the pie-chart displays the strength of evidence in favour of memory improvement (H1) or no memory improvement (H0). The median effect size and 95% Bayesian credibility interval are indicated in the top right. Panel C: Bayesian sequential analysis illustrates the consistency of findings cross participants. The plot displays how the Bayes Factor changes with each additional participant. Each grey circle represents the data from a single participant, presented in the order of data collection. The smaller dots (defined in the top right) show that the outcome is not dependent on choice of prior. The pie-chart displays the relative strength of evidence in favour of memory improvement (H1) compared to evidence in favour of no effect (H0). Panel D: Memory enhancement is not specific to items closest to boundaries. Panel E: Conditional Response Probability (CRP) as a function of lag. Participants show no significant change in lag+1. Error bars represent ± 1 standard error of the mean.

Panel A: Recall performance for 40 words presented as 1 continuous list (non-segmented learning) was compared to recall performance for 4 lists containing 10 words, segmented with salient moments of change (segmented learning). Analysis revealed that there was no significant difference in the proportion of words remembered between the non-segmented condition (M = 0.33; SD = 0.11) and the segmented condition (M = 0.35; SD = 0.13). As shown in Figure 13(B), with a Bayes factor $BF_{10} = 0.31$ the analysis provides 'anecdotal' evidence that presenting ten-word in packets segmented by salient moments of change within a virtual environment does not lead to an increase in the amount of information that can be remembered.

Panel B: Prior and Posterior of the Bayesian analysis reported under Panel A.

Panel C: Bayesian analysis was conducted to examine the build-up of evidence across our participants. Sequential analysis confirms that 7 out of 11 participants provided evidence in favour of the null hypothesis. While the overall evidence is in favour of null effect, not all participants provided evidence in favour of the null hypothesis, suggesting that for some, but not all participants, ten words between boundaries does may not exceed working memory capacity. To further investigate the nature of the segmentation effect we carried out two additional analyses shown in Panels D and E, both of which examined whether the structure of the to-be-remembered information influenced memory.

Panel D: Analysis of performance for boundary and non-boundary words revealed a difference in performance for boundary and non-words even though the evidence suggests that there is no increase in the number of words recalled. These data were subjected to Bayesian repeated measures ANOVA with factors of segmentation (segmented vs non-segmented) and position (boundary vs non-boundary. The Inclusion Bayes Factor for segmentation was $BF_{incl} = 0.39$, indicating 'anecdotal' evidence in favour of the null. The inclusion Bayes Factor for position was $BF_{incl} = 5.36$, indicating 'moderate' evidence in favour of a significant difference between boundary and non-boundary words. The inclusion Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 0.8$, indicating 'anecdotal' evidence in favour of a null effect for an interaction. For Experiment 5 the results suggest that there are no increases in the number of words recalled when presenting packets containing ten-words. However, there are differences in performance between boundary and non-boundary words, suggesting that segmentation is affecting memory performance.

Panel E: Finally, Conditional Response Probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words. Analysis of CRP revealed that there was no significant difference in Lag+1 between the non-segmented condition ($M = 0.05$; $SD = 0.52$) and the segmented condition ($M = 0.14$; $SD = 0.21$). As shown in Figure 13, with a Bayes factor $BF_{10} = 0.82$ the analysis provides 'moderate' evidence that presenting words in packets consisting of 10 words (across multiple identical grey rooms, segmented by spatial-temporal gaps and the presence of doorways) within a virtual environment does not result in an increase in recalling the words in the order of presentation.

Additional analysis was conducted to determine whether the pattern of remembering exhibited clustering, consistent with the structure imposed during encoding, using the Adjusted Ratio Clustering (ARC) method (Senkova & Otani, 2012; Pettijohn *et al.*, 2016). ARC scores are based on the number of recalled items, the number of category repetitions and the number of recalled categories, indexing the extent to which recalled words were clustered by the locations they were originally presented in. The words between boundaries in the segmented condition were compared to words in an equivalent position in the non-segmented condition. Average ARC scores were calculated using every 4 words as a category for both the non-segmented and segmented conditions, revealing a higher degree of clustering when words were segmented during learning ($ARC = 0.26$; $SE = 0.176$) than when non-segmented ($ARC = 0.1$; $SE = 0.27$), $BF_{10} = 1.35$. This analysis suggests that when structure was introduced (via changes in spatial-temporal context due to moving between rooms) the words that were subsequently recalled were clustered according to the locations in which they were presented during the study phase. The ARC scores therefore provide evidence showing that the words were encoded as a sequence of events, tied to a location and segmented by boundaries.

Discussion

The results of Experiment 5 support the conclusions drawn from Experiment 4. The memory benefits of segmentation may indeed by governed by working memory capacity. While for Experiment 5, memory performance for boundary words was greater than non- boundary words for ten-word packets, previous work identified no significant benefit for boundary words when presenting ten-word packets (Pettijohn *et al*., 2016). The results of Experiment 5 showed no significant improvement in recall when comparing an unsegmented condition to a segmented condition consisting of four packets of ten-words. Whereas previous work has shown a significant improvement in recall for a segmented condition consisting of ten-word lists. The differences in results may support the theoretical view of an unreliable working memory capacity. Ten words may be within the upper limit for the participants of the study by Pettijohn *et al*., (2016) whereas ten-word lists may have exceeded the upper limit for the participants of Experiment 5. In both cases, participants are showing benefits of segmentation. When working memory is overloaded between boundaries, words from the middle of a list may be lost, resulting in a significant difference in boundary and non-boundary words. If working memory is not overloaded between boundaries, then there is an overall improvement in the number of words recalled and no significant difference between boundary and non-boundary words. The results of Experiment 5 also showed no significant improvement in memory for clustering or temporal order, again suggesting that working memory may have been overloaded between boundaries.

Following the results of Experiment 5, Experiment 6 aimed to confirm the theoretical interpretation that improved performance in episodic recall is due to the segmentation of working memory packets. Experiment 6 reduced the number of words presented between boundaries in the segmented condition from ten words to eight words. The prediction for Experiment 6 was that reducing the number of words between boundaries would result in no significant difference between boundary and non-boundary words along with an overall improvement in recall performance and memory for clustering and temporal order.

6.3 Experiment 6

The aim of Experiment 6 was to examine whether an improvement in the proportion of words recalled provided by segmentation depends on whether the quantity of information between boundaries may be maintained within working memory. Specifically, While Experiment 5 compared two conditions, each of which exceeded working memory capacity, Experiment 6 compared two conditions, one of which was within a working memory capacity of seven plus or minus two items (Miller 1956). Experiment 6 employed the same virtual environment as Experiment 5, all rooms were the same size, shape and colour, and participants were automatically moved between locations. While in Experiment 5 there was a significant drop in the number of non-boundary words recalled when compared to boundary words, no overall improvement for the proportion of words recalled was found. Consequently, Experiment 6 compared performance when forty words were presented within one location, to performance when eight words were presented per location split across a total of five locations. With eight words between boundaries, participants may be better able to benefit from segmentation.

Methods

Participants

A total of 20 participants, with age range 18-32 years (M = 21.1; SD = 3.2) were recruited through the University of Stirling online recruitment portal, and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling General University Ethics Panel.

Procedure

Materials

The materials used were the same as in Experiment 5.

Procedure

The procedure used was the same as in Experiment 5, with participants automatically moved along the same route, travelling along an open corridor with a sequence of left and right turns.

Statistical Analysis

The analysis used the same measures as in Experiment 5.

Results

The results of Experiment 6 are shown in Figure 14, demonstrating significant memory improvement effects when information is split into working memory packets.

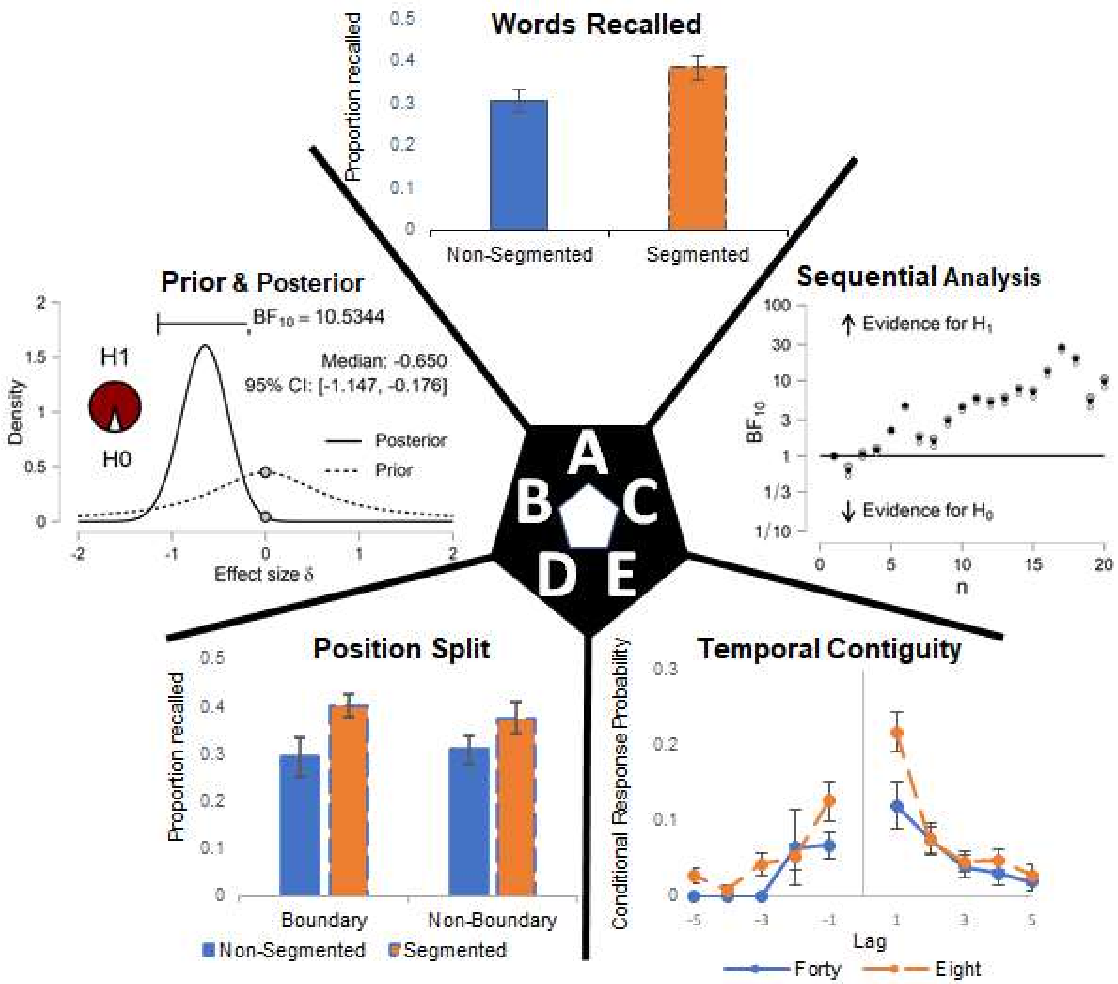

Figure 14, Panel A. Proportion of words recalled for Eight (8 words in 5 locations) versus Four (4 words per location across 10 locations). Panel B: Plot of Bayesian prior and posterior for the analysis of Experiment 6. Panel C: Bayesian sequential analysis. Panel D: Memory improvement is not specific to items closest to boundaries. Panel E: Conditional Response Probability (CRP) as a function of lag. Participants show no evidence for an increase in lag+1.

Panel A: Recall performance for 40 words presented as 1 continuous list (non-segmented learning) was compared to recall performance for 5 lists containing 8 words, segmented with salient moments of change (segmented learning). Analysis revealed that there was a significant difference in the proportion of words remembered between the non-segmented condition (M = 0.31; SD = 0.11) and the segmented condition (M = 0.38; SD = 0.13). This is illustrated in Figure 14, panel A with a Bayes factor BF_{10} = 10.5 the analysis provides 'strong' evidence that presenting words in packets segmented by salient moments of change within a virtual environment leads to an increase in the amount of information that can be remembered.

Panel B: Prior and Posterior of the Bayesian analysis reported under Panel A.

Panel C: Bayesian analysis was conducted to examine the build-up of evidence across our participants, illustrated in Figure 14, panel C. Sequential analysis confirms that 12 out of 20 participants provided evidence in favour of the alternative hypothesis. While the overall evidence is in favour of an improvement, not all participants benefitted from the segmented condition, suggesting that for some, but not all participants, 8 words between boundaries exceeds their capacity for taking advantage of segmentation.

Panel D: The pattern of performance for words that were presented adjacent to a boundary or occurred between boundaries. Results are illustrated in Figure 14 panel D. These data were subjected to Bayesian repeated measures ANOVA with factors of segmentation (segmented vs non-segmented) and position (boundary vs non-boundary). The Inclusion Bayes Factor for segmentation was $BF_{incl} = 16.8$, indicating 'strong' evidence in favour of segmentation. The inclusion Bayes Factor for position was $BF_{incl} = 0.23$, indicating 'anecdotal' evidence in favour of a null effect for position. The inclusion Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 0.19$, indicating 'anecdotal' evidence in favour of a null effect for an interaction. For Experiment 6 the results suggest that the improvements provided by segmentation were due to an increase for both boundary and non-boundary words.

Panel E: Finally, Conditional Response Probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words. Analysis of CRP revealed that there was no significant difference in Lag+1 between the non-segmented condition (M = 0.12; SD = 0.14) and the segmented condition (M = 0.22; SD = 0.12). These results are illustrated in Figure 14 panel E. With a Bayes factor $BF_{10} = 3.05$ the analysis provides 'moderate' evidence that presenting words in packets consisting of 8 words (across multiple identical grey rooms, segmented by spatial-temporal gaps and the presence of doorways) within a virtual environment, results in an increase in recalling the words in the order of presentation.

An additional analysis was conducted to determine whether the pattern of remembering exhibited clustering, consistent with the structure imposed during encoding, using the Adjusted Ratio Clustering (ARC) method (Senkova & Otani, 2012; Pettijohn *et al*., 2016).

The words between boundaries in the segmented condition were compared to words in an equivalent position in the non-segmented condition. Average ARC scores were calculated using every 8 words as a category for both the non-segmented and segmented conditions, revealing a higher degree of clustering when words were segmented during learning (ARC = 0.52; SE = 0.08) than when non-segmented (ARC = 0.22; SE = 0.07), $BF_{10} = 11.6$. This analysis suggests that when structure was introduced (via changes in spatial-temporal context due to moving between rooms) the words that were subsequently recalled were clustered according to the locations in which they were presented during the study phase. The ARC scores therefore provide evidence showing that the words were encoded as a sequence of events, tied to a location and segmented by boundaries.

3.3. Discussion

We questioned whether long-term memory performance could be improved when presenting segmented words lists, each of which overload the previously reported five-item hard limit of working memory capacity. Contrary to expectations, participants did show an increase in number of words recalled and clustering by segment when presenting 8 words between event boundaries defined by moments of change within a virtual learning environment. The analysis of temporal contiguity also found evidence in favour of an increase in memory for temporal order. The results suggest that participants are recalling the words both in the packets of original presentation and in the temporal order of original presentation. In a previous study, presenting 10 words between boundaries resulted in a significant drop in performance for non-boundary words in comparison to boundary words (M. Logie & Donaldson, 2021). Whereas the present experiment found no difference in performance between boundary and non-boundary words when presenting 8 words between boundaries. The results are consistent with a working memory capacity of 7 plus or minus 2 (Miller, 1956) and inconsistent with a hard limit of 3-5 domain-general items (Cowan, 2010; Cowan, Morey & Naveh-Benjamin, 2021). In addition to an increase in words recalled, the improvements in clustering and memory for temporal order also support the view that long-term learning may depend on experiencing segmented working memory packets.

The results are also consistent with the view that working memory capacity may depend on time-limited resources (Barrouillet & Camos, 2015; 2021). Previous work in support of a time limited, domain-specific view can be found in studies comparing native speakers of different languages. Native Chinese speakers show an increased digit and word span in comparison to native English speakers (Stigler, Lee & Stevenson, 1986; Mattys, Baddeley & Trenkic, 2018). The phonological codes in Mandarin take less time to articulate than in English and more words may be maintained within working memory when the words take less time to articulate. When rehearsal is limited via the use of articulatory suppression (repeatedly speaking unrelated words aloud) span is reduced (Chincotta & Underwood, 1997). However, participants are still capable of recalling words, suggesting that the rehearsal of phonological codes is not a prerequisite for the ability to recall words. Similarly in studies employing articulatory suppression with visual spatial arrays (R.Logie, 2009; Shimi & R. Logie 2019) the unavailability of distinct phonological codes requires participants to depend on solely visual-spatial representations which may impair long-term learning performance. These studies suggest that capacity limits may be supported by phonological and visual-spatial codes. If phonological codes are unavailable, they may be reconstructed from encoded images. If visuo-spatial codes are unavailable, they may be reconstructed from encoded phonological codes. However, depending on the method of testing and the availability of different strategies it is possible that not every participant will do so (Belletier *et al*., 2021; Forsberg, Johnson & R. Logie, 2020; Forsberg *et al*., 2020).

The present experiment provided words of high imageability. Participants showing improvements may benefit from maintaining phonological codes as well as the generation of visual-spatial representations. Participants showing no improvements may either take longer to articulate the presented words or fail to generate images of what the words represent. We return to the question of the availability of visuospatial imagery in Experiment 10. As an alternative interpretation, the participants showing no difference may already efficiently segment the presented content even when boundaries are not provided. Event Segmentation has been identified as an automatic process (Kurby & Zacks, 2008) and the results of the current experiment may suggest that providing pre-segmented event sequences can improve memory performance for participants who inefficiently segment information. The results may also suggest that for some participants, presenting eight words between boundaries exceeds working memory capacity and limits the potential benefits of segmentation. Following on from Experiment 6, therefore, we questioned whether benefits may be found by comparing two segmented conditions, both of which provide a word list between boundaries that may be maintained within the potential limits of working memory. Under these circumstances, would the differences in memory performance disappear?

6.4 Experiment 7

Presenting eight words between boundaries resulted in an improvement in number of words recalled, clustering and temporal contiguity but no differences in performance between boundary and non-boundary words. However, not all participants provided evidence in favour of an increase in the number of words recalled. Following the results of Experiment 6, we conducted another experiment to explore the optimisation of long-term learning based on the presentation of segmented working memory packets. Presenting segmented lists containing 8 words may provide a benefit as a result of being within working memory capacity limits for some participants. Would a greater proportion of participants provide evidence in favour of an improved long-term memory performance when comparing segmented word lists that straddle a working memory capacity of 5 items? If working memory capacity can be defined by a 7 plus or minus 2 item limit (Miller, 1956) we may expect no differences in performance when comparing two conditions of segmented word packets, both of which can be maintained within working memory. Experiment 7 made use of the same virtual environment as Experiment 6 and compared 8 words in 5 locations to 4 words in 10 locations. If some participants are unable to benefit from segmented 8-word packets would a greater proportion of participants show an increase in words recalled, clustering and temporal contiguity when presented with 4-word packets?

Methods

Participants

A total of 16 new participants, with age range 18-27 years (M = 20.3; SD = 2.6) were recruited through the University of Stirling online recruitment portal, and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling General University Ethics Panel.

Materials

The materials used were the same as in Experiment 5.

Procedure

The procedure used was the same as in Experiment 5, with participants automatically moved along the same route, travelling along an open corridor with a sequence of left and right turns.

Statistical analysis

The analysis used the same measures as in Experiment 5.

Results

Experiment 7 demonstrated a significant memory improvement effect when information is split across multiple locations. As shown in Figure 15, segmented 4-word lists do provide further benefits in comparison to segmented 8-word lists.

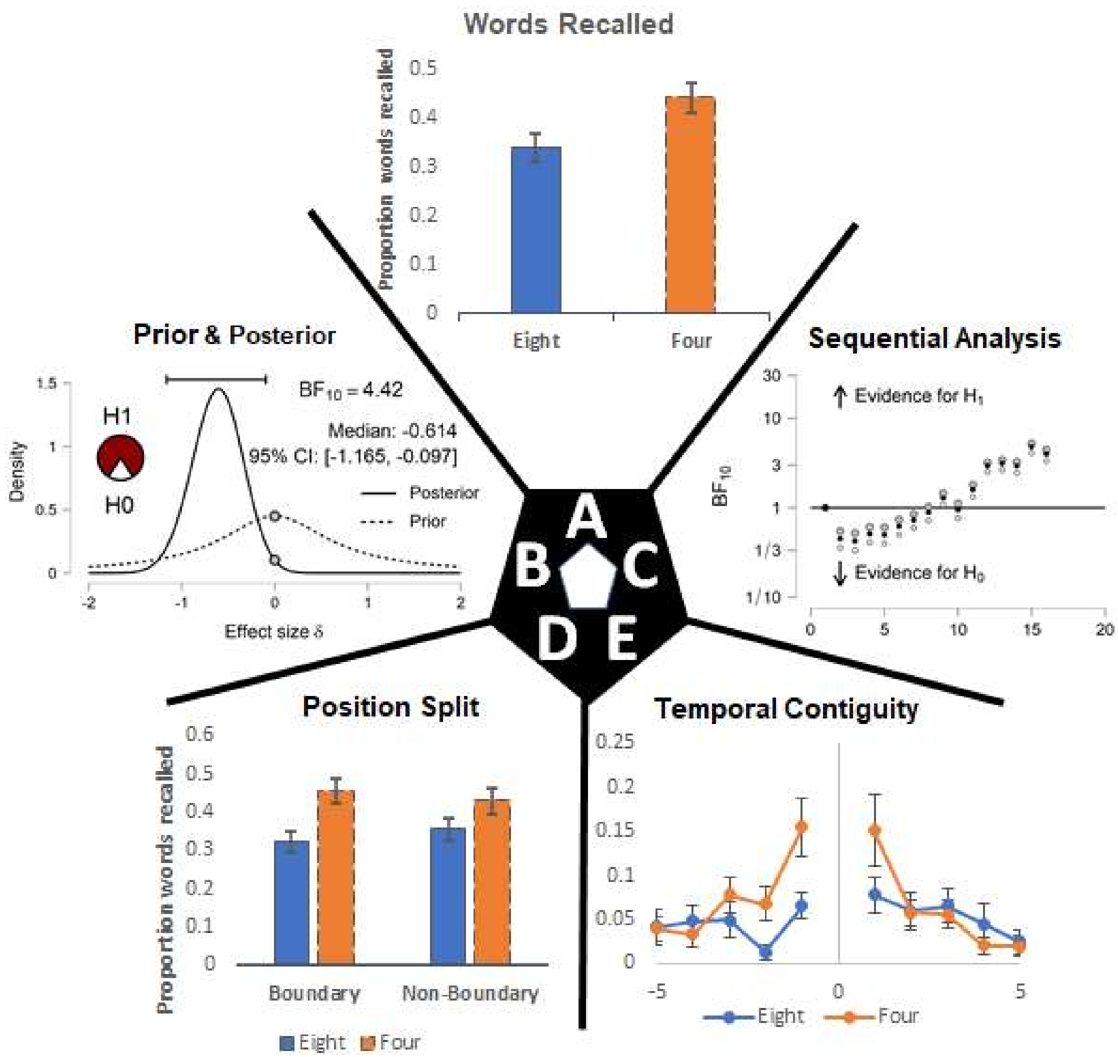

Figure 15, Panel A. Proportion of words recalled for Eight (8 words in 5 locations) versus Four (4 words per location across 10 locations). Panel B: Plot of Bayesian prior and posterior for the analysis of Experiment 7. Panel C: Bayesian sequential analysis. Panel D: Memory improvement is not specific to items closest to boundaries. Panel E: Conditional Response Probability (CRP) as a function of lag. Participants show no evidence for an increase in lag+1.

Panel A: The number of words recalled for 8 words presented in 5 location was compared to the number of words recalled for 4 words per location across 10 locations. Results are illustrated in Figure 15, Panel A. There was a significant difference in the number of words remembered between 8-word packets (M = 0.34; SD = 0.03) and 4-word packets (M = 0.44; SD = 0.03) conditions ($BF_{10} = 4.42$). In this case there is 'moderate' evidence to show that presenting words in packets that can be maintained within working memory across multiple locations, segmented by spatial-temporal gaps without the presence of doorways within a virtual environment provides a benefit to the number of words that can be remembered.

Panel B: Prior and Posterior of the Bayesian analysis reported under Panel A.

Panel C: The Bayesian sequential analysis illustrated in Figure 15, Panel C shows that 9 out of 16 participants provided evidence in favour of the alternative hypothesis, that 4-word lists provided a benefit for free recall compared with 8-word lists, although this was not true for all participants. Nevertheless, the results support the view that presenting segmented working memory packets can lead to improved long-term memory performance.

Panel D: Further analysis examined whether the improvement was due to boundary words (the first and eighth word when presenting eight-word packets and the first and fourth word when presenting four-word packets) versus non-boundary words (the second through seventh word for eight-word packets and the second and third words presented for four-word packets). Results are illustrated in Figure 15, Panel D. These data were subjected to Bayesian repeated measures ANOVA with factors of segmentation (four boundaries for eight-word packets versus nine boundaries for four-word packets) and position (boundary versus non-boundary words). The Bayes Factor for segmentation was $BF_{incl} = 33.45$, indicating 'extreme' evidence in favour of segmentation. The Bayes Factor for position was $BF_{incl} = 0.28$ indicating 'moderate' evidence in favour of a null effect for position. The Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 0.53$ indicating 'anecdotal' evidence in favour of a null effect for the interaction. The results suggest that the improvements provided by segmentation were due to better free recall when the 40-word list was presented as four-word packets than when presented as eight-word packets, and this was true for both boundary and non-boundary words.

Panel E: The results of the CRP are illustrated in Figure 15, Panel E. This analysis revealed that there was no significant difference in Lag+1 between the eight-word segment list (M = 0.078; SD = 0.082) and the four-word segment list (M = 0.151; SD = 0.163). With a Bayes factor $BF_{10} = 0.92$ the analysis provides 'inconclusive' evidence in favour of an effect for an improvement in memory for temporal order when comparing segmented 8-word lists to segmented 4-word lists.

Finally, average ARC scores were calculated using every 8 words as category in the 8-word condition and every 4 words as a category in the 4-word condition. The ARC scores demonstrated evidence in favour of an increase in clustering from few boundaries for eight-word packets (ARC = 0.18; SE = 0.098) to many boundaries for four-word packets (ARC = 0.46; SE = 0.10) conditions ($BF_{10} = 47.89$). The ARC scores suggest that the words were encoded as a sequence of events, tied to a location, and segmented by spatial-temporal gaps. Presenting 4 words provided significant benefits to clustering over the presentation of 8 words.

Discussion

Experiment 7 found evidence suggesting that segmenting lists of words with spatial-temporal gaps results in an increased number of words being available for episodic recall for many smaller packets than for fewer larger packets. Experiment 7 also identified an increase in the clustering of recalled words by location of presentation for four-word packets than for eight-word packets. Participants appear to be encoding the word list packets presented between boundaries as individual clusters or packets, further supporting the view that event boundaries act as triggers for episodic encoding. However, while there was an increase in clustering, Experiment 7 found no evidence in favour of a difference between small and large packets in terms of the tendency for participants to recall temporal order of items in the list, even if the instructions were for free recall. For the current paradigm, improvements in memory for temporal order were found in Experiment 6 when comparing an unsegmented condition to a segmented condition with 8 words between boundaries. In Experiment 7 no differences were found in memory for temporal order when comparing eight-word packets and four-word packets. Although participants are asked to conduct free recall, the results of experiment 7 suggest that participants may spontaneously recall the words in the order of presentation if the number of words between boundaries may be maintained within working memory. In Experiment 7 there was a significant drop in the proportion of words recalled for the condition that exceeds a working memory capacity of five items. There was no significant drop in memory for temporal order however, suggesting that even when working memory capacity is exceeded and participants lose items, memory for temporal order is not necessarily impacted even with 8-word packets.

The results from this experiment suggest that there might not be a hard domain-general limit of 3-5 items for information that can be held within working memory. If a hard limit exists then we might expect to find clear improvements in words recalled, clustering and temporal order for every participant for packets of three-five items compared with packets of eight items. Not all participants showed improvement for four-word lists compared with eight-word lists. For Experiment 6 it is possible that some participants showed no differences between an unsegmented forty-word list and five eight-word packets due to both conditions exceeding their individual working memory capacity. However, for Experiment 7 we again found that some participants showed no differences, even though there was an overall effect for the group. It is also possible that some participants were spontaneously and covertly segmenting the forty-word lists, even when not presented as a series of packets. In this respect the results support the view of segmentation as an automatic process (Kurby & Zacks, 2008). If this is the case, some participants are already efficiently segmenting working memory packets and providing salient segmentation would not necessarily improve long term memory performance. The effects of segmentation may be most beneficial for individuals who inefficiently segment, or do not segment the items spontaneously.

Our results thus far are consistent with the view that encountering a moment of change by travelling to a new location may act as a trigger to encode the words maintained within working memory into longer term storage. Task performance may depend on speed of articulation for maintenance, the availability of generated visual-spatial images for highly imageable words, and the experience of detecting change defining an event boundary. The results also provide further evidence in support of the view that segmenting working memory packets provides benefits to long-term learning without the need for repetition employed in Hebbian learning. Detecting change, imposed by moving to a new location after the presentation of to-be learned content, results in an improved long-term memory performance.

Nonetheless, the results of Experiment 7 leave open the question of whether presenting even smaller packets would result in further improvements in recall, and this was addressed in Experiment 8.

6.5 Experiment 8

Following the results of Experiment 7 we conducted a further experiment to compare segmented word lists that were both within a working memory capacity of 5 items. Previous reports suggest the capacity of working memory acts as a bottleneck, providing an upper limit on the benefits for long-term learning. We have established that rather than long-term memory performance being dependent on maintaining information within working memory and repeating arrays, overloading working memory between event boundaries defined by highly salient moments of change can impair long-term memory performance. However, in both Experiment 6 and 7 a similar proportion of participants provided no evidence in favour of an increase in the number of words recalled. Furthermore, in Experiment 7 when presenting 8-word packets and 4-word packets we found increased clustering of the recalled words, but no difference in the memory for temporal order. If working memory capacity can be defined by a five-item domain-general limit (Cowan, 2010) we may again expect no differences in performance when comparing two conditions of segmented word packets, both of which can be maintained within working memory. Consequently, Experiment 8 compared performance for five words in eight locations to one word in forty locations. If working memory capacity provides only an upper limit for the quantity of information recalled, then we may expect to find no differences when providing two conditions where the number of words between boundaries may be maintained within working memory.

Methods

Participants

A total of 20 participants with age range 18-38 (M = 20.9, SD = 4.9) were recruited through Stirling University's online recruitment portal, course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling general university ethics panel.

Materials

The materials used were the same as in Experiment 7.

Procedure

Study phase

The experiment involved a study phase presenting 5 words between boundaries, followed by a test phase and a study phase presenting 1 word between boundaries, followed by a test phase. In the 5-word condition words were displayed one at a time in a random order at a random point on a 4 by 4 grid within a single location in the virtual environment. The words were displayed for 3 seconds with a 1 second gap between them. For the 1-word condition 1 random word was presented at a random point on a 4 by 4 grid across 40 total locations. After the study phase there was a two-minute gap to allow for some forgetting and so the last words presented were no longer being held in working memory.

Test phase

The test phase used the same procedure as in Experiment 7.

Results

Experiment 8 once again demonstrated significant memory improvement effects when information is split into packets. The memory improvement effect found in Experiments 6 and 7 was still present without participants passing through doorways or travelling through space.

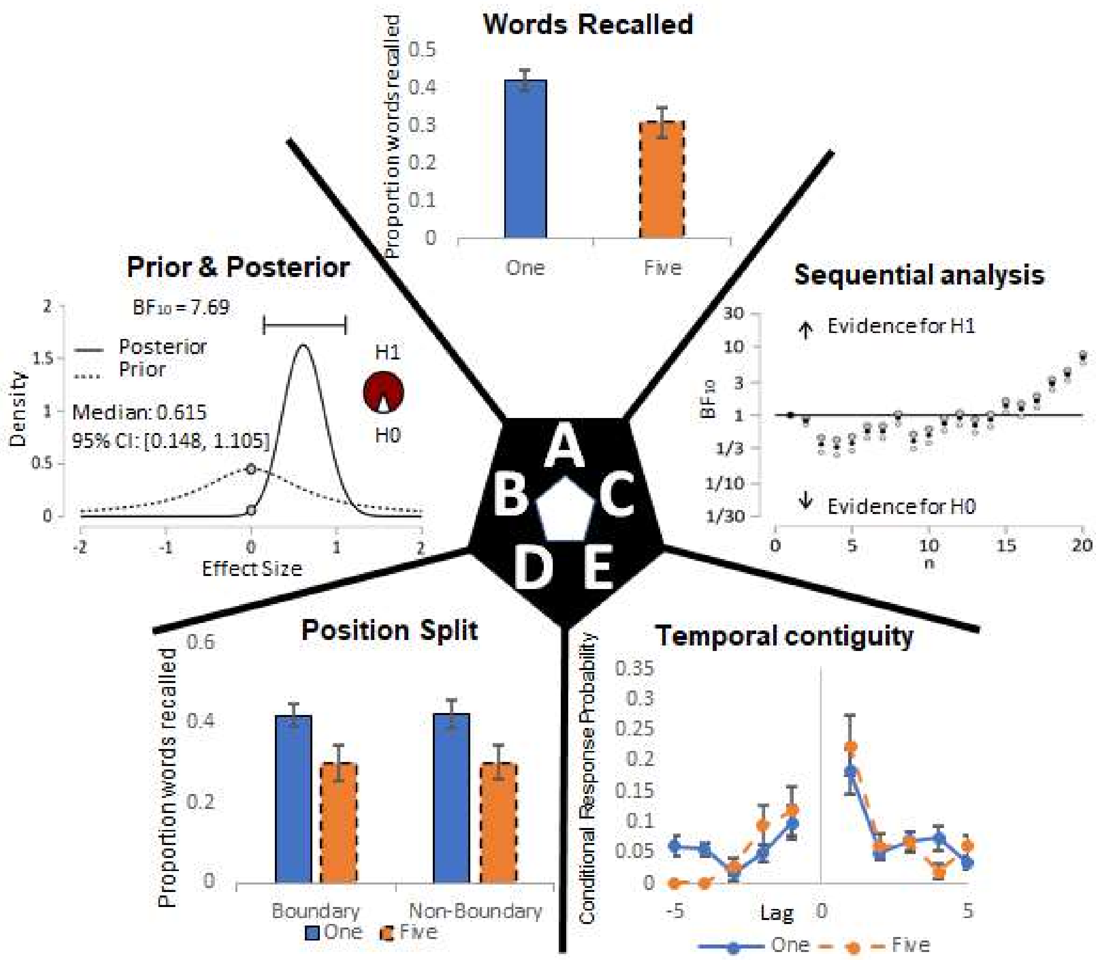

Figure 16, Panel A. Proportion of words recalled for One (1 word per location across 40 locations) versus Five (5 words per location across 8 locations). Panel B: Plot of prior and posterior for Experiment 8. Panel C: Bayesian sequential analysis. Panel D: Memory performance split for boundary and non-boundary words. Panel E: Probability of recalling the words in correct temporal order represented by Lag +1.

Panel A: The number of words recalled for 5 words presented in one packet was compared to the number of words recalled for 1 word per packet across 40 packets segmented by spatial-temporal gaps. There was a significant difference in the number of words remembered between the Five-word condition (M = 0.3; SD = 0.18) and the One-word condition (M = 0.42; SD = 0.13) conditions ($BF_{10} = 7.69$). The result provides 'moderate' evidence for a benefit to the number of words that can be remembered when segmenting packets of words with temporal gaps.

Panel B: Prior and Posterior of the Bayesian analysis reported under Panel A.

Panel C: The Bayesian sequential displays that 12 out of 20 participants provided evidence in favour of the alternative hypothesis. Presenting 1-word packets leads to significant memory improvement, although not all participants display a difference.

Panel D: Further analysis examined whether the improvement was due to boundary words (the first and fifth word presented at each location) or non-boundary words (the second, third and fourth words presented at each location). Boundary and non-boundary words for the one-word condition were defined as the equivalent first and fifth positions as the 5-word condition. These data were subjected to Bayesian repeated measures ANOVA with factors of packet size (1-word vs 5-word) and position (boundary vs non-boundary). The Bayes Factor for packet size was $BF_{incl} = 232$, indicating 'extreme' evidence for segmentation. The Bayes Factor for position was $BF_{incl} = 0.22$, indicating 'anecdotal' evidence in favour of a null effect for position. The Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 0.28$, indicating 'anecdotal' evidence against an interaction. For Experiment 8 analysis suggests that the improvements provided by segmentation were not tied to boundaries.

Panel E: Conditional response probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words. Analysis of CRP revealed that there was a significant difference in Lag+1 between the 1-word condition (M = 0.18; SD = 0.17) and the 5-word condition (M = 0.22; SD = 0.22). As shown in Figure 16, with a Bayes factor $BF_{10} = 0.29$ the analysis provides 'moderate' evidence in favour of a null effect for an improvement in memory for temporal order.
Finally, as in previous experiments, Adjusted Ratio Clustering (ARC) scores were calculated. Using every 5 words as a category for both conditions. There was substantial evidence in favour of an increase from the one-word condition (ARC = 0.31; SE= 0.06 compared to Five-word condition (ARC = 0.66; SE= 0.07) condition ($BF_{10} = 26.84$). The recalled words were clustered by the packets, segmented in time, that they were presented in during the study phase. For the one-word condition, the analysis suggests that participants are not clustering adjacent words into events.

Discussion

Further reducing the number of words between boundaries again resulted in an increase in the number of words recalled. However, once again, not every participant showed an increase in the number of words recalled. The differences in clustering suggest that there may be benefits to providing events containing multiple words up to the limit of working memory capacity, independent from the number of words recalled. There was no difference in memory for temporal order, suggesting that memory for temporal order may only drop when comparing conditions that are well above and within working memory capacity. In addition, our previous work has highlighted that memory for temporal order can be impaired when imposing prediction errors. The results of the present study provide further evidence that memory for words recalled, clustering and memory for temporal order are dependent on packets defined by salient moments of change. In the one-word condition each event is defined by a single word and may be encoded as such. However, based on the Bayesian analysis, not every participant showed a difference in the number of words recalled. The pattern of results suggests that for some participants one-word events and five-word events are encoded just as effectively. There may indeed be a 'goldilocks zone' with peaks in performance for words recalled, clustering and memory for temporal order when segmented events make use of existing working memory capacity. The results of Experiment 8 support the theoretical account of long-term learning benefitting from the segmentation of packets that may be maintained within working memory.

Following the results of Experiment 8 we questioned whether there was a lower limit for the size of the packets between boundaries to influence long-term learning. The results of Experiment 8 suggested that five items between boundaries exceeded working memory capacity. To confirm that the capacity limit of working memory influenced long-term memory performance, we compared two conditions, each of which presented packets to words that could be maintained within a working memory capacity of less than five items.

6.6 Experiment 9

Previous research has suggested that the capacity of working memory acts as a bottleneck, providing an upper limit on the benefits for long-term learning (Forsberg, Guitard & Cowan, 2021). We have provided evidence that rather than long-term memory performance being dependent on maintaining information within working memory and repeating arrays, the presence of boundaries is an important component in supporting the transfer of information from working memory into long-term memory. Our data from Experiments 5 and 6 suggest that, at a group level, overloading working memory with a large number of items between event boundaries defined by highly salient moments of change can impair long-term memory performance. However, in both experiments a similar proportion of participants provided no evidence in favour of an increase in the number of words recalled. Furthermore, in Experiment 7 we found increased clustering of the recalled words for four-word packets compared with eight-word packets, however no difference in the memory for temporal order. If working memory capacity can be defined by a 3-5-item domain-general limit (Cowan, 2010) we may again expect no differences in performance when comparing two conditions of segmented word packets, both of which can be maintained within working memory. Consequently, Experiment 9 compared performance for four words in ten locations with one word in 40 locations. Working memory capacity may provide an upper limit for the quantity of information presented between boundaries supporting the availability of information for delayed recall. If so, we may expect to find no differences when providing two conditions where the number of words between boundaries may be maintained within working memory. However, it may be the case that underloading working memory with one-word per segment could also reduce long-term episodic encoding compared with four-word packets that are close to the assumed capacity limit for working memory.

Methods

Participants

A total of 21 participants with age range 18-41 ($M = 20.76$, $SD = 4.9$) were recruited through Stirling University's online recruitment portal, course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling general university ethics panel.

Materials

The materials used were the same as in Experiment 5, however participants were moved through 40 locations in one condition and through ten locations in the other condition. The segmented condition employed equivalent spatial-temporal gaps for each word segment as used in Experiments 5 and 6.

Procedure

Study phase

The experiment involved a study phase presenting four words between boundaries, followed by a test phase and then a study phase presenting one word between boundaries, followed by a test phase. In the four-word condition words were displayed one at a time in a random order at a random point on a four by four grid across a total of ten locations in the virtual environment. The words were displayed for 3 seconds with a 1 second gap between them. For the one-word condition one random word was presented at a random point on a 4 by 4 grid across 40 total locations. After the study phase there was a two-minute gap to allow for some forgetting and so the last words presented were no longer being held in working memory.

Test phase

The test phase used the same procedure as in Experiment 5.

Results

Experiment 9 found inconclusive evidence for a difference in memory performance when comparing four-word packets and one-word packets. The memory improvement effects between different packet lengths found for comparison of longer packets in Experiments 6, 7 and 8 were no longer present.

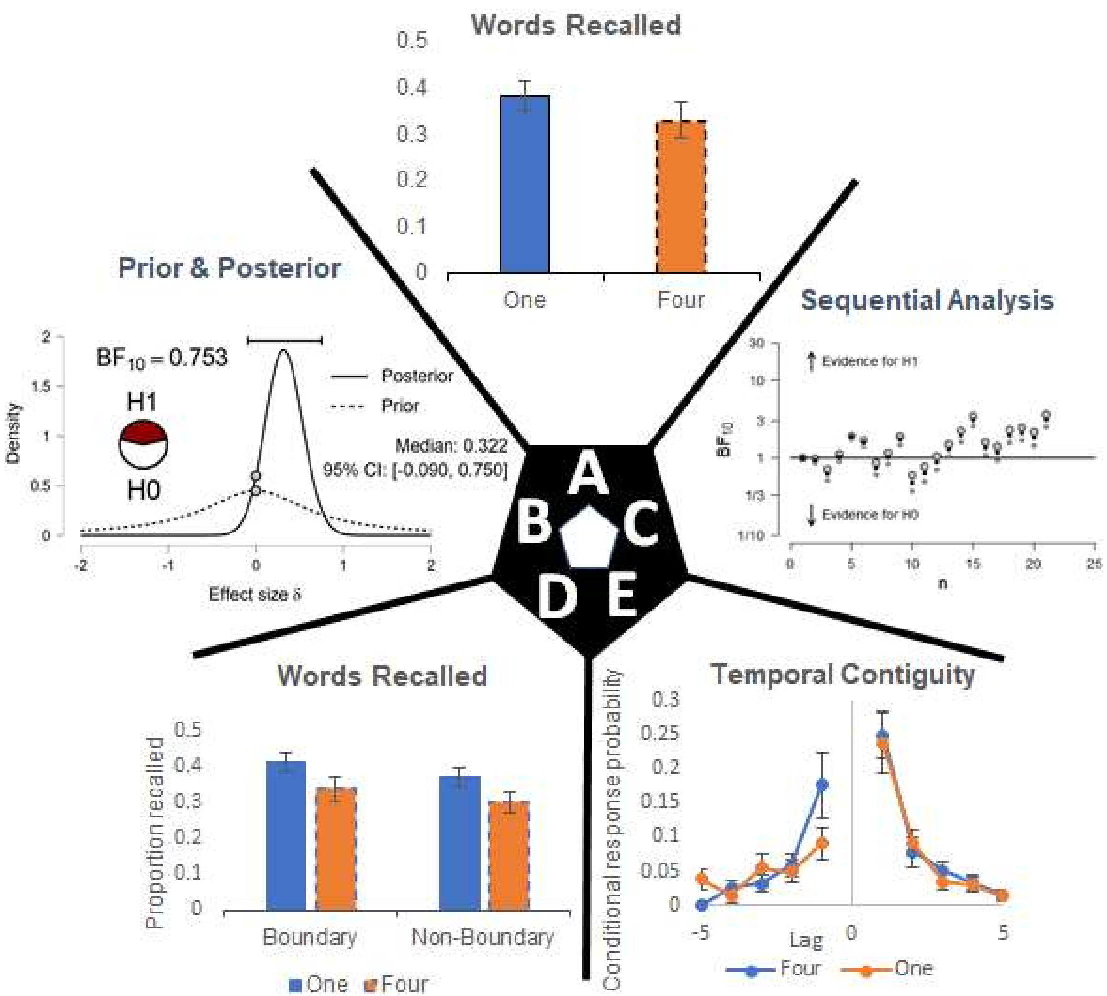

Figure 17, Panel A. Proportion of words recalled for One (1 word per location across 40 locations) versus Four (4 words per location across 10 locations). Panel B: Plot of prior and posterior for Experiment 9. Panel C: Bayesian sequential analysis. Panel D: Memory performance split for boundary and non-boundary words. Panel E: Probability of recalling the words in correct temporal order represented by Lag +1.

Panel A: The number of words recalled for 4 words presented in one segment was compared to the number of words recalled for 1 word per segment across 40 packets segmented by spatial-temporal gaps. There was no significant difference in the number of words remembered between the One-word condition (M = 0.38; SD = 0.14) and the Four-word condition (M = 0.32; SD = 0.18) (BF_{10} = 0.75). The result provides 'anecdotal' evidence for a difference in the number of words that can be remembered when comparing segmented 4-word packets and segmented 1-word packets.

Panel B: Prior and Posterior of the Bayesian analysis reported under Panel A.

Panel C: The Bayesian sequential analysis displays that 11 out of 21 participants provided evidence in favour of the alternative hypothesis. The analysis suggests that there is an almost equal split between participants recalling more words with 1-word packets and participants recalling more words with 4-word packets.

Panel D: Further analysis examined whether there were differences in performances for boundary words (the first and fourth word presented at each location) or non-boundary words (the second and third words presented at each location). Boundary and non-boundary words for the one-word condition were defined as the equivalent first and fourth positions as the 4-word condition. These data were subjected to Bayesian repeated measures ANOVA with factors of packet size (1-word vs 4-word) and position (boundary vs non-boundary). The Bayes Factor for segmentation was $BF_{incl} = 1.54$, indicating 'inconclusive' evidence for packet size. The Bayes Factor for position was $BF_{incl} = 0.30$, indicating 'anecdotal' evidence in favour of a null effect for position. The Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 0.47$, indicating 'anecdotal' evidence against an interaction. For Experiment 9, analysis suggests that the improvements provided by segmentation were not tied to boundaries.

Panel E: Conditional response probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words. Analysis of CRP revealed that there was evidence in favour of a null effect for Lag+1 between the One-word condition ($M = 0.24$; $SD = 0.2$) and the Four-word condition ($M = 0.25$; $SD = 0.16$). With a Bayes factor $BF_{10} = 0.23$ the analysis provides 'anecdotal' evidence in favour of a null effect for an improvement in memory for temporal order.
Finally, as in previous experiments, Adjusted Ratio Clustering (ARC) scores were calculated. Using every 4 words as a category for both conditions. There was evidence in favour of an increase from the one-word condition (ARC = 0.37; SE= 0.34 compared to Four-word condition (ARC = 0.62; SE= 0.38) condition ($BF_{10} = 3.97$). The recalled words were clustered by the packets, segmented in time, that they were presented in during the study phase. For the one-word condition, the analysis suggests that participants are not clustering adjacent words into 4-word events, however when presenting 1 word between boundaries, every word could be encoded as a single event.

Discussion

When comparing two conditions that were below the previously assumed working memory capacity limit of five items, participants did not show a significant difference in the proportion of words available for delayed recall. The results suggest that both conditions may have been presenting word packets that could be maintained within working memory. The differences in clustering suggest that there may be benefits to providing events containing multiple words up to the limit of working memory capacity, independent from the number of words recalled. There was evidence in favour of no difference in memory for temporal order suggesting that memory for temporal order may only drop when the quantity of information presented between boundaries greatly exceeds working memory capacity. In addition, previous work (Horner, Bisby, Wang, Bogus & Burgess, 2016; M.Logie & Donaldson, 2021) (see Chapter 5) has highlighted that memory for temporal order can be impaired when imposing prediction errors driven by the presence of doorways. The results of the present study provide further evidence that memory benefits for words recalled, clustering and memory for temporal order are dependent on packets defined by salient moments of change. In the one-word condition each event is defined by a single word and may be encoded as such. However, based on the Bayesian analysis, some participants showed evidence in favour of four-word packets and some participants showed evidence in favour of one-word packets. There may indeed be a 'Goldilocks zone' with peaks in performance for words recalled, clustering and memory for temporal order when segmented events make use of existing working memory capacity, but that 'Goldilocks zone' might differ between participants.

Taken together, and at a group level, Experiments 5 ,6 ,7 and 8 support the view that limiting the quantity of information between boundaries with salient moments of change provided by moving between locations, results in an improved long-term memory performance. Nevertheless, we again found that some participants did not provide evidence in favour of improvements. The results support the view of segmentation as an automatic process (Kurby & Zacks, 2008), presenting segmented working memory packets may be most beneficial for participants who inefficiently segment information. There were no significant differences between boundary and non-boundary words for Experiments 6-8 when presenting four- or eight-word packets. However, previous work did find significant differences between boundary and non-boundary words when presenting ten-word packets (M.Logie & Donaldson, 2021)(see Chapter 5). The results suggest that there may be an unreliable limit with an increasing probability of losing items furthest from the boundaries as list lengths increase. Beneficial effects of presenting segmented working memory packets may depend on individual differences in temporally limited working memory capacity, speed of processing and the ability to detect change. As a further alternative, the results are also consistent with an ongoing context drift (Howard & Kahana, 2002; Hitch, Flude & Burgess, 2009). Specifically, items that appear close together share a greater contextual overlap and beneficial grouping effects may not be dependent on the presence of event boundaries. Future work may be required to further distinguish between event segmentation and context drift.

The previous Experiments explored capacity limits in line with a domain general limit of 3-5 items. Participants may have benefitted to varying degrees by the availability of both phonological and visuospatial codes from highly imageable words. We conducted one further experiment to examine performance when limiting the availability of visuospatial based strategies by using words of low imageability.

6.7 Experiment 10

Following the results of Experiments 5-9, one final experiment was conducted to identify whether the memory benefits of segmentation would remain when limiting the availability of visuospatial codes. The multicomponent model of working memory proposes separable domain-specific capacity limits for phonological, visual and spatial information. If working memory is full to capacity for phonological information, capacity still remains for visuospatial information. An alternative account proposes an embedded processes domain general system (Cowan, 1999, 2016, 2019). From this perspective there are not separable capacities for domain specific stimulus (e.g., phonological, visuospatial) and capacity can be explained by a general-purpose attentional system.

Experiment 10 made use of words of low imageability and compared a segmented condition above working memory capacity to a segmented condition within working memory capacity. Overloading working memory capacity between boundaries with highly imageable words resulted in a drop in long-term memory performance. If there is a domain general capacity limit, we may expect to find similar results to the first three experiments even when limiting the availability of visuospatial information. However, if there are multiple components that can independently support domain-specific information then we may expect a reduced long-term memory performance. Based on a previous study (M.Logie & Donaldson, 2021)(see Chapter 5) the over-capacity condition presented 10 words per location across 4 locations while the under-capacity condition presented 5 words per location across 8 locations. While we expected poorer long-term memory performance when employing words of low imageability the improvements due to segmentation should still be present. If transfer of domain-specific information from working memory to long-term storage is dependent on event boundaries defined by moments of change then we would expect to find an increase in the number of words recalled. Would the benefits of one-shot segmented learning still be present even when limiting the availability of visuo-spatial codes?

Methods

Participants

A total of 13 new participants, age range 19- 21 years: M = 19; SD = 0.91) were recruited through the University of Stirling online recruitment portal, and course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling general university ethics panel.

Procedure

Experiment 10 made use of the same virtual learning environment as Experiment 9. In the over-capacity condition 40 words were randomly presented at 10 words per location in 4 total locations. In the under-capacity condition 40 words were randomly presented at 5 words per location in 8 total locations. The words used in the experiment were taken from the MRC Psycholinguistic database (Coltheart, 1981), and every word had a maximum imageability rating of one standard deviation below the mean.

Results

Experiment 10 once again demonstrated a significant memory improvement effect when information is split into packets that may be maintained within working memory, in this case packets consisting of 5 words provided improvement over packets consisting of 10 words.

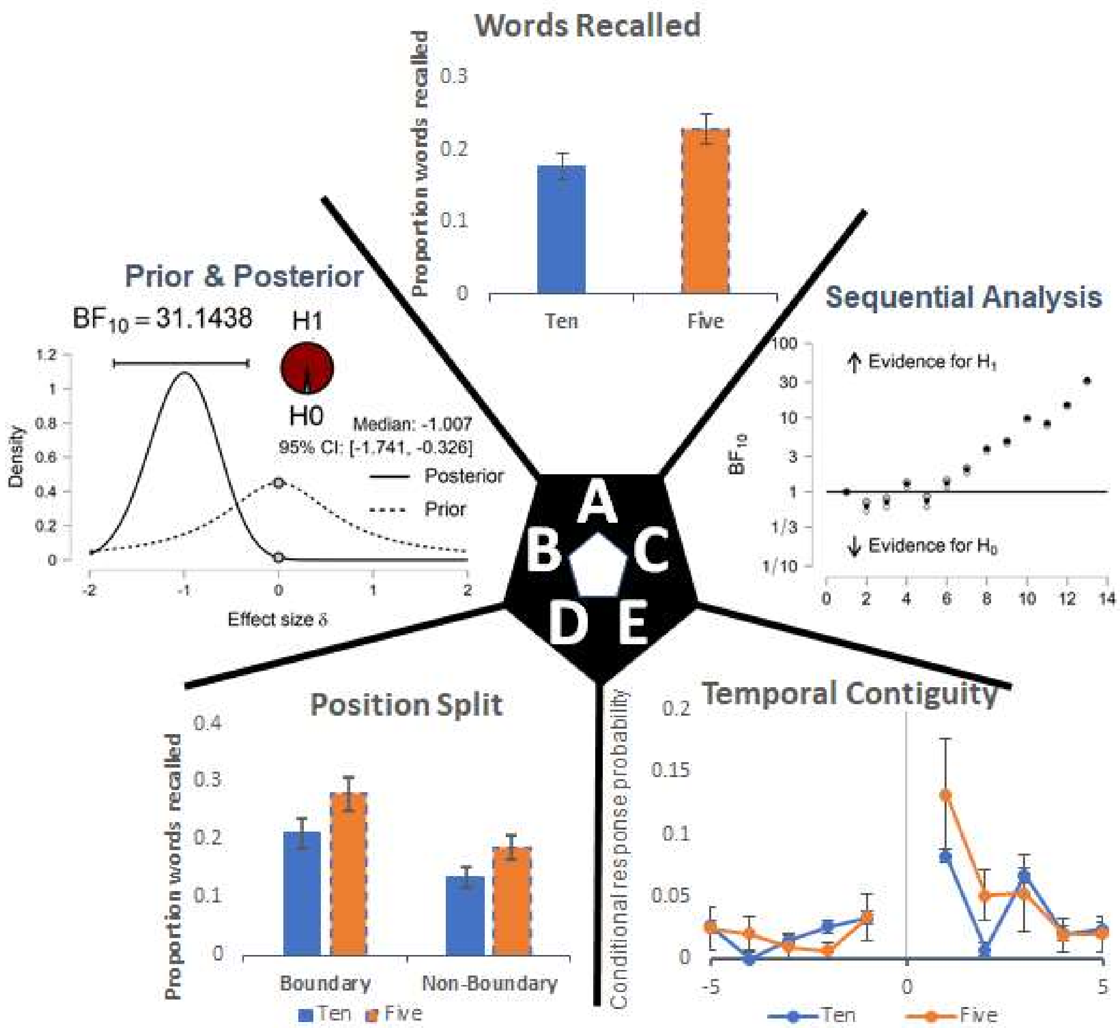

Figure 18, Panel A. Proportion of words recalled for Ten words (10 words per location across 4 locations) versus Five words (5 words per location across 8 locations). Panel B: Plot of prior and posterior for experiment 10. Panel C: Bayesian sequential analysis. Panel D: Memory improvement effect due to an increase in non-boundary words recalled. Panel E: Conditional Response Probability (CRP) as a function of lag. Participants show no evidence for an increase in lag+1.

Panel A: The number of words recalled was recorded. There was a significant difference in the number of words remembered between over-capacity (M = 0.18; SD = 0.07) and under capacity (M = 0.23; SD = 0.07). Analysis revealed a BF_{10} of 31.14, providing 'strong' evidence that presenting 5 words per location across 8 locations resulted in more words being remembered than 10 words per location across 4 rooms.

Panel B: Prior and Posterior of the Bayesian analysis reported under Panel A.

Panel C: Bayesian sequential analysis indicated that 9 out of 13 participants provided evidence in favour of the alternative hypothesis: presenting segmented packets of information leads to significant memory improvement.

Panel D: Further analysis examined whether the improvement was due to boundary words (the first and fifth word presented at each location) or non-boundary words (the second and third and fourth words presented at each location). Figure 18(D) displays the recall performance for boundary and non-boundary words. These data were subjected to Bayesian repeated measures ANOVA with factors of packet size (10-word vs 5-word) and position (boundary vs non-boundary). The Bayes Factor for segmentation was $BF_{incl} = 4.69$, indicating 'moderate' evidence for packet size. The Bayes Factor for position was $BF_{incl} = 25.59$ indicating 'strong' evidence in favour of position. The Bayes Factor for an interaction between position and segmentation was $BF_{incl} = 1.26$ indicating 'anecdotal' evidence in favour of an interaction. As can be seen in Figure 18, when the availability of visuospatial information is restricted, there is a significant drop in memory performance for non-boundary words. The drop is present even when the number of words presented between boundaries (in this case 5 words) may be maintained within working memory.

Panel E: Conditional response probability analysis (CRP) was conducted to examine the potential effect of segmentation on the temporal contiguity of the recalled words. Analysis of CRP revealed that there was no significant difference in Lag+1 between the Ten-word condition (M = 0.08; SD = 0.13) and the Five-word condition (M = 0.13; SD = 0.16). As shown in Figure 18, with a Bayes factor $BF_{10} = 0.36$ the analysis provides 'weak' evidence in favour of no difference in memory for temporal order. Presenting 5 low imageability words between boundaries does not benefit memory for temporal order in comparison to presenting 10 low imageability words between boundaries.

Finally, analysis was conducted to determine the effect of presenting packets of words segmented in time. Adjusted Ratio Clustering (ARC) scores were calculated using every 5 words as a category for both the overcapacity (ARC = 0.27; SE = 0.23) and under capacity (ARC = 0.39; SE = 0.13 conditions. Analysis revealed 'weak' evidence ($BF_{10} = 0.31$) in favour of no increase in clustering. When the availability of visuospatial information is limited there is no significant increase in clustering when providing segmented working memory packets.

Discussion

While overall performance was poorer when employing words of low imageability, the benefits of segmentation were still present, in terms of number of words recalled. However, for Experiment 6,7 & 8 there were no significant differences between boundary and non-boundary words when presenting eight- or four-word packets of highly imageable words between boundaries. Whereas for Experiment 10, when presenting words with low imageability there is a drop in memory performance for non-boundary words for both 10-word packets and 5-word packets. In addition, there were no differences in clustering or memory for temporal order. The results suggest that the availability of visuospatial and semantic representations are critical components for the presentation of segmented working memory packets to aid in the optimisation of long-term learning. When presented with highly imageable words participants may be generating visuospatial images or scenes for each word segment. In Experiment 10 when limiting the availability of visuospatial scenes there is a corresponding limitation in the amount of information encoded from working memory into longer-term storage. Participants may be limited to the use of phonological, lexical, and semantic codes and are unable to benefit from visuospatial information associated with the words.

6.8 Interim General Discussion

The results of the experiments reported in the present study suggest that information maintained within working memory may be encoded into longer-term storage upon encountering salient moments of change that may be defined by spatial-temporal gaps. The first three experiments suggest that over loading working memory between event boundaries defined by salient moments of change will result in an impaired long-term memory performance. The results are consistent with previously reported findings of working memory capacity (Miller, 1956; Cowan, 2010; R. Logie, 2011). However, based on Bayesian analysis, the majority of participants appear to display an improved memory performance in words recalled, clustering and memory for temporal order when presented with events consisting of 8 highly imageable words. There is a significant increase in words recalled when presenting 8 words in 1 location in comparison to 40 words in 1 location. There is a significant increase in words recalled when presenting 4 words per location in 10 locations in comparison to 8 words per location. However, there is an inconclusive difference when comparing 4 words per location in 10 locations and 1 word per location in 40 locations.

There may not be a hard domain general capacity limit of 5 items, and working memory capacities may instead be governed by temporally limited resources (Barrouillet & Camos, 2015) and depend on whether or not visuo-spatial associations as well as phonological lexical, and semantic information can be encoded for the words (e.g. R.Logie, 2011; Paivio, 1969, 1971, 1986). The results also support the important influence of event boundaries, with predictable moments of change provided by travelling between locations within a virtual environment (M. Logie & Donaldson, 2021). However, in addition to identifying a reduced performance when providing too many words between boundaries, Experiment 10 found a reduced recall performance when limiting the availability of visuospatial information. Both over and under-loading working memory between event boundaries can result in an impaired long-term memory performance. The tenth experiment made use of words of low imageability and the benefits of segmentation were still present, with more words recalled that were presented next to a boundary than non-boundary words.

The important influence of imageability for memory is well established (Paivio, 1969, 1986). Without readily imageable words between boundaries, long term memory performance also dropped. The results are consistent with Dual-Coding theory (Paivio, 1986), and theories of multimedia learning (Mayer, 2002, 2009). An interpretation of the present study is that working memory can generate distinct mnemonic representations of phonological, visual, spatial and semantic information. I argue that encountering an event boundary acts as a trigger to encode temporally synchronous representations held within working memory into longer-term storage. Moreover, we would argue that long-term learning is a creative process, not purely a passive accumulation process. I will now discuss further evidence in favour of this interpretation as well as future implications for understanding the relationship between working memory and long-term learning.

Traditionally the Hebb repetition effect (Hebb, 1961) shows an improvement in immediate serial recall following multiple repetitions of verbal information at recurring moments during an experiment. An original interpretation suggests that multiple repetitions lead to a build-up of an episodic trace and associated long-term learning. However, an alternative theoretical account is that encountering an event boundary acts as a trigger for episodic encoding (McClelland, 1994; Radvanksy, 2017; Zacks, 2020) and fine-grained event boundaries may be defined by salient moments of change (M. Logie & Donaldson, 2021). On this argument, the absence of a learning effect for change detection with repeatedly presented visuo-spatial arrays (R.Logie et al., 2009; Shimi & Logie, 2019) can be explained in terms of the absence of event boundaries. This offers a potential reason why the contents of working memory are lost trial to trial and appear to leave no, or a very weak episodic trace to support learning, even although the same stimulus array is repeated. Arrays of colourful shapes may be temporarily held within a short-term visual cache (R. Logie, 1995), and in the absence of a salient moment of change the information is wiped from working memory without being encoded into longer term storage. Presenting highly similar visual-spatial arrays with subtle changes and the use of articulatory suppression to prevent the use of phonological codes, allows for the maintenance of only visuo-spatial information segmented with weak event boundaries. Therefore, many multiple repetitions will be required before there is evidence of long-term learning.

In the present study, spatial-temporal gaps provided highly salient moments of change relative to the presentation of word lists. However, event boundaries may be most effective when the salient moment of change requires resources distinct from the to-be-remembered information. I would predict similar benefits in memory for sequential navigational routes segmented with words (e.g., second star to the right, and straight on till morning). Navigational landmarks must be perceptually salient (e.g., Denis, 2018; Yesiltepe *et al*., 2020) and as such may be interpreted as a subset of event boundaries, because landmarks provide moments of change. The present study suggests that multiple repetitions found in Hebbian learning are not the only way to improve long-term learning. Travelling between locations in a virtual environment provides highly salient moments of change for the segmentation of working memory packets, which allows for efficient, one-shot, long-term learning.

The present study provides evidence in favour of working memory as a separate imaginative construction system, with moments of change providing triggers for episodic encoding. Further support for the importance of event boundaries can be found in a study combining behavioral and neuroimaging techniques, identifying hippocampus activation at event boundaries provided in film clips (Sinclair *et al*., 2021, see also Ben-Yakov & Henson, 2018). Expected boundaries at the end of a scene aided in establishing memories. Notably, in the Sinclair *et al*. study, prediction errors, imposed by interrupting a clip before the original ending of the film, led to a disruption in memory for temporal order and an increase in false memories. Further behavioural work has examined the effect of overloading working memory between prediction errors imposed by passing through doorways in a virtual environment (McFadyen *et al*., 2021). Participants are more likely to incorrectly remember information that was not initially presented if working memory is overloaded between boundaries during study. The result would support the proposal that memory may be reconstructive in nature (Bartlett, 1931; Braine, 1965; Pollio & Foote, 1971; Loftus & Pickrell, 1995). Upon remembering an event, the size of the gap between boundaries may indicate that more information was initially presented than was encoded, and participants subsequently show an increased false alarm rate as an attempt to fill the gaps.

Working memory may be able to create new mnemonic representations to fabricate events that did not originally occur without an individual being aware that a particular event memory may be a fabrication (Loftus, 1997). Consistent with this view, previous work provides evidence suggesting that individuals with high working memory capacity demonstrate a lower susceptibility to false memories (Gerrie & Garry, 2007; Watson *et al*., 2005). An alternative interpretation based on segmentation is that the incidence of false memories may depend on the density of domain-specific information presented between boundaries relative to working memory capacity. Incidence of false memories may also depend on whether information is segmented with expected moments of change, or unexpected prediction errors. Furthermore, a memory system that reconstructs and fabricates novel mnemonic representations into event sequences that do not yet exist necessarily must consist of more than activated long-term memory (Norris, 2019). Reconstructing a past event and fabricating a future or fictitious event may both depend on adaptive constructive process (Schacter, 2012). Working memory may be a system for generating simulations of both the past and the future and the simulations can themselves be encoded into long-term storage. There may be an advantage in the ability to discard simulations that do not provide moments of change or prediction errors as the simulation can already be recreated from existing long-term storage.

Working memory may maintain copies of information taken from perception and activated long term memory to construct new episodes (R. Logie, 2011). If event boundaries are not experienced, then the maintained information will not be encoded. This interpretation is consistent with the findings of both Shimi & R. Logie (2018) and Forsberg *et al*., (2020). However, while Forsberg *et al*., (2020) propose the concept of working memory as a bottleneck for episodic encoding, the term bottleneck speaks only to an upper limit for information that is present within working memory and does not account for the varying availability of representations that incorporate a wider range of codes, such as a visual image or semantic associates, nor the importance of event boundaries as triggers supporting long-term learning. Recent work has highlighted that when attempting to solve a problem or answer a question, individuals will overlook subtractive changes (Adams, Converse, Hales & Klotz, 2021) removing items may be more effective than adding items although individuals will tend to attempt to solve problems by adding items. Many studies of working memory capacity focus on identifying an upper limit by adding information until performance drops. The present study demonstrates how limiting the availability of a range of memory codes available (e.g., low-imageable words) can help to identify the lower limits for the contributions of working memory capacity to long-term learning. While exceeding an upper limit will be detrimental for long term learning, under-loading working memory between boundaries will also result in an impaired long-term memory performance.

In addition to the implications for working memory capacity and long-term learning, I propose an alternative account to the episodic buffer component of working memory proposed by Baddeley (2000). Information that is temporally synchronous within working memory may be encoded into longer term storage upon an encounter with an event boundary (M.Logie & Donaldson, 2021) (see Chapter 5). While awareness of an event boundary will support faster learning, information may be maintained within domain specific buffers and encoded upon experiencing an event boundary, without the need for awareness (Wuethritch, Hannula, Mast, Henke, 2017), consistent with the original experiments reported by Hebb (1961). Furthermore, recent work has argued that episodic memory may be composed of multiple layers of temporally limited memory buffers (Hasson, Chen & Honey, 2018; Chien & Honey, 2019). Similarly, Andermane, Joensen & Horner (2021) identified that memories for episodic events are represented across multiple levels. The results of tests of memory may depend upon which levels are being tested and whole events may be encoded and forgotten in a 'holistic' manner. From this perspective the episodic buffer proposed by Baddeley (2000;

see also Badeley, Hitch & Allen, 2021; Karlsen, Allen & Hitch, 2010) could instead be defined as a layer of episodic memory with the shortest temporal limit. Single events are generated within working memory. Event boundaries may be encountered at both a fine and coarse grain (Kurby & Zacks, 2008). Experiencing a fine-grained event boundary, such as a perceptual moment of change, triggers the encoding of an event into a temporally limited layer of episodic memory that can store a sequence of multiple events. Future work may be able to determine whether encountering coarse-grained event boundaries, defined by either a moment of change or prediction error, may trigger the encoding of event sequences into successively longer lasting layers of episodic memory.

Recent work in studies of segmentation has led to the conclusion that episodic memory for a recent event could be defined as memory for any information that occurred prior to the most recently encountered event boundary (Zacks, 2020; M. Logie & Donaldson, 2021). If unpredictable endings or the experience of moments of change act as triggers for episodic encoding, then studies that identify a domain general slot-limit for working memory may instead be testing the reconstruction of information from episodic memory after the information maintained within working memory has been encoded. The bottleneck for episodic encoding may depend on the size of the event that can be encoded and not on the quantity of domain specific information that can be simultaneously maintained within working memory. Further support in favour of this interpretation comes from the established view that episodic recall is a reconstructive process (Bartlett, 1932; Schacter *et al*., 2008), working memory could be viewed as a scene construction system for the creation of event sequences (Hassabis & Maguire, 2007, 2009). The approach of presenting segmented working memory packets, employed in the present study, may provide an alternative means of identifying the limits of working memory. I propose the existence of a 'Goldilocks zone' for episodic encoding, delineated by event boundaries, that can both generate accurate, and fabricate fictitious, distinct mnemonic representations composed of phonological, visual, spatial, and semantic information. If working memory is filled to capacity in one dimension between boundaries, capacity remains for other dimensions to be filled. If there is too much information between boundaries the information furthest from the boundaries may be lost according to an increasing probability. If there are unfilled gaps in working memory between boundaries, then additional information may be fabricated during recall, drawing on schemata in semantic memory. Responding to working memory tests may depend on the generation of mnemonic representations delineated by event boundaries after episodic encoding has occurred.

Can working memory be trained? Previous work has proposed that working memory training may depend on developing novel routines that may be employed to complete tasks (Norris, Hall & Gathercole, 2019; Norris, Holmes & Gathercole, 2019). The results of the present study suggest that memory training could also depend on the ability to establish novel event boundaries. When learning any task one beneficial aim could be to identify moments of change and establish anchor points to segment task relevant content into working memory packets. Learning to establish anchor points could provide a fruitful approach to training segmentation ability, benefiting task performance regardless of how related subsequent tasks are to the initial method of training. While developing a method of training segmentation ability may prove to be effective, the present study demonstrates that providing pre-defined working memory packets segmented in space and time within a virtual environment benefits long-term learning. Future work may seek to further define the presence of a 'goldilocks zone' defined by segmented working memory packets for the optimisation of long-term learning. The current study also suggests that long-term learning may be improved by providing educational content as segmented working memory packets in virtual environments. An effective method of cognitive training may involve engaging in creative activities by generating novel segmented mnemonic representations.

7. General Discussion

I will now provide an overview of the present findings. I will first restate the original aims and provide a summary of the reported experiments before discussing further theoretical implications. I will then end with the limitations of the current research and outline future directions. The current thesis had two major aims. Firstly, to determine whether presenting segmented working memory packets within a virtual Method of Loci paradigm can provide memory improvement effects without training. Secondly, I sought to identify components that are important for defining the presence of event boundaries and more specifically to determine the importance of prediction errors that have been proposed to be driven by the presence of doorways (Pettijohn *et al*., 2016; Zacks, 2020). Finally, I aimed to make use of the identified components to determine whether episodic encoding could be optimised by manipulating the quantity and domain of information presented between boundaries, in line with working memory capacity limits about which different working memory theories are broadly in agreement, even if theories differ in the details as to why those limitations arise (for reviews see R.Logie, Camos & Cowan, 2020).

Do Doorways really matter

The aim of Experiment 1 was simply to determine whether a memory improvement effect could be found when presenting word lists, segmented by prediction errors, driven by the presence of doorways within a virtual environment. The results of Experiment 1 established that presenting segmented word lists (four words in each of ten locations) did provide a memory improvement effect compared with an unsegmented list (40 words in one location). This was true not only for the number of words recalled but also in clustering of the words by the location of presentation during recall. However, there was no difference between the two presentation conditions in memory for temporal order.

Following Experiment 1 I aimed to determine whether the presence of doorways was a crucial component for driving the memory benefits, as has been argued by Pettijohn *et al.* (2016). Experiment 2 employed the same virtual environment as Experiment 1, again comparing four words across ten locations with 40 words in one location, but with the walls and doorways between locations removed. Even without virtual walls and doorways, Experiment 2 replicated the memory benefit effects from segmenting word lists as had been found in Experiment 1. That is, Experiment 2 further revealed that when word lists were segmented by spatial-temporal gaps without passing through doorways there was moderate evidence in favour of an improvement in memory for temporal order, providing stronger evidence in favour of an improvement in memory for temporal order than the anecdotal results found in Experiment 1. The contrast between these first two experiments suggests that prediction errors, driven by the presence of doorways, may have a specific effect of disrupting memory for temporal order (M. Logie & Donaldson, 2021) (see Chapter 5).

Experiment 3 again employed the same virtual environment and sought to identify whether memory improvement effects for segmented lists versus non-segmented lists would still be found without the spatial boundaries imposed by the movement between locations. In this case segmentation was achieved by inserting temporal gaps between word groups, but all words were presented in the same location within the virtual environment. Temporal gaps between groups of four words alone were found to produce memory benefits, compared with presenting all 40 words with the same inter-word interval. The observed benefit was similar to that found with combinations of spatial and temporal gaps in Experiments 1 and 2. Overall, the results suggested that the benefits of segmentation driven by the presence of event boundaries may depend on the salience of the event boundary rather than solely reliant on the concepts of space and time. While Event Segmentation Theory stresses the importance of the presence of boundaries defined by prediction errors, memory performance may be improved based on temporal clustering because items that occur close in time may share a greater contextual overlap. Temporal clustering and the presence of salient moments of change may provide the memory benefits found in studies of segmentation without the presence of prediction errors.

The first three experiments compared forty words in one location, with four words per location in ten locations. Experiment 4 compared two segmented conditions to explore to what extent memory performance was tied to the quantity of information presented between boundaries. Experiment 4 compared ten words per location in four locations, with five words per location in eight locations. The results suggested that there may be an optimal limit of no more than five words for the quantity of information presented between boundaries that may depend on working memory capacity. When ten words were presented in each location there was a significant difference between boundary and non-boundary words. The difference between boundary and non-boundary words suggests that there may not be a hard capacity limit. If working memory is overloaded between boundaries there may be an increasing probability of losing items furthest from the boundaries as list lengths increase.

Identifying a goldilocks zone

Based on the initial experiments, memory improvement effects may be found when presenting word packets segmented by boundaries defined by spatial-temporal gaps within a virtual environment. Memory improvement effects were found without the prediction errors driven by the presence of doorways. Having established the components required to define a boundary for finding memory improvement effects, I sought to make use of the same virtual environment to identify the outer bounds of benefits to memory performance based on the quantity and domain of information presented between boundaries.

Based on previous reports employing ten-word lists (Pettijohn et al., 2016) and previously reported working memory capacity of seven plus or minus two items (Miller, 1956), Experiment 5 compared forty words in one location to ten words in four locations.

There was no overall difference between conditions in the proportion of words recalled. However, in the segmented condition, there was significantly better recall of words closest to the boundary between word groups compared with non-boundary words. The results further support the findings of Experiment 4 suggesting that when exceeding working memory capacity between boundaries the items furthest from the boundaries may be unavailable for recall but being close to a boundary provides an advantage.

In Experiment 6 I compared forty words in one location to eight words in five locations. Based on a working memory capacity of three to five items I did not expect to find a benefit in recall from segmented lists, because presenting eight words between boundaries would exceed working memory capacity for each word group. However, memory performance was better overall in the segmented compared with the unsegmented condition in terms of number of words recalled, clustering and memory for temporal order. In contrast with Experiments 4 and 5, in Experiment 6 no significant difference was found between boundary and non- boundary words when presenting eight words between boundaries. Experiments 4 and 5 generated evidence that ten-word packets resulted in significant differences between boundary and non-boundary words. The results of Experiment 6 suggested that eight-word packets do not produce significant differences between boundary and non-boundary words. However, segmenting into eight-word compared with forty-word packets did provide a benefit to memory. From Experiments 4, 5, and 6, if the number of items in each packet greatly exceeds working memory capacity (ten items), then any segmentation benefit seems to appear for words close to the boundaries, but again, the number of words recalled from each packet is within the assumed capacity limit of working memory. In sum, it appears that for packets of eight items or less, there is an overall benefit for recalling words within each packet. For packets of ten items, any benefit of segmentation appears for words close to the segmentation boundaries. These observations are consistent with the suggestion that working memory capacity may place an important constraint on encoding in, and recall from, episodic memory. The findings also are consistent with the proposal that encoding is facilitated by segmenting long word lists into shorter packets, even if only some of the items within each packet are recalled.

Having found evidence for the benefits of segmenting word packets for episodic recall, Experiment 7 sought to identify the outer bounds of these benefits. If working memory capacity may be assumed to comprise three to five items (such as words), then a comparison of an above working memory capacity condition (eight-word packets) to a within working memory condition (four-word packets) should produce the same memory improvement effects as Experiment 6. The results of Experiment 7 showed a similar improvement in the proportion of words recalled and clustering for four-word, compared with eight-word packets, suggesting that eight-word packets may exceed the optimum grouping size for episodic encoding, that is working memory capacity. However, there was no significant difference between boundary and non-boundary words suggesting that being close to a packet boundary does not offer any episodic recall advantage for eight-word or four-word packets. In addition, there was no difference between conditions in recall of temporal order. The results are consistent with a working memory capacity of three-five items being the optimum packet size for episodic recall. However, there may not be a hard limit as I might also have expected a difference between boundary and non-boundary words and an improvement in memory for temporal order if eight-word packets exceed working memory capacity.

Experiment 8 explored further the boundaries of the benefits of list segmentation for episodic recall by comparing five-word packets to one-word packets for a list of 40 words. There was a significant benefit for one-word packets in the overall proportion of words recalled. There was a significant increase in clustering when presenting five-word packets compared with one-word packets. The difference in clustering suggests that one-word packets are encoded as individual segmented events and were not clustered with neighbouring one-word packets. There was again no difference between boundary and non-boundary words, and evidence in favour of a null effect for a difference in memory for temporal order. These results suggest that linking a one-word packet with each location in the virtual environment (as used in the traditional Method of Loci) does offer some benefit for recall compared with multiple words per packet.

For a final attempt to explore the limits of the segmentation benefits, in Experiment 9 I compared four-word packets and one-word packets. If both conditions may be comfortably maintained within working memory, I may expect that there would be no differences following tests of delayed free recall. There was no significant difference in the proportion of words recalled, suggesting that both conditions were indeed within the optimum size of packet for episodic encoding and recall, which is interpreted here as working memory capacity. There was an increase in clustering for four-word packets, again suggesting that one-word packets may be encoded as single events by themselves. There were again no significant differences between boundary and non-boundary words and evidence for the null between conditions regarding memory for temporal order.

One further possibility is that the capacity limit for the quantity of information presented between boundaries may also depend upon the type of information presented, as well as the number of items within each segmented packet. In Experiment 10 I used words of low imageability to limit the availability of visual-spatial information. Also, building on the results of Experiment 4 I compared ten-word packets to five-word packets. There was a significant increase in the proportion of words recalled for five-word packets compared with ten-word packets. Unlike the results of Experiment 4, there were no differences in clustering or memory for temporal order. Experiment 4, when employing words of high imageability, found significant differences between boundary and non-boundary words for ten-word packets but not for five-word packets. In Experiment 10 there were significant differences between boundary and non-boundary words for both ten-word and five-word packets. The availability of visual-spatial information appears to provide crucial support for the encoding of working memory packets.

The Experiments provided evidence that episodic encoding may be optimised by presenting a long list of words as segmented packets, each of which comprises sublists of words that are within the assumed capacity of working memory. The differences in proportion of words recalled, boundary and non- boundary words, clustering and memory for temporal order had different breakpoints. The results suggest that when each packet exceeds working memory capacity, participants may be strategic in encoding only as many items as their working memory capacity allows. With packets of five to eight highly imageable words, participants appear to encode and recall from anywhere within each packet, to cluster their recall according to the packet structure of presentation, and to preserve some information about temporal order of presentation, even if the instructions are for free recall. For packets of ten items, or for packets of five low-imageable words, participants appear to encode items that are close to packet boundaries. Therefore, the optimum packet size for episodic encoding, that is assumed to be linked with the capacity limit of working memory may depend on the type of information presented. Tests of working memory capacity tend to focus on immediate tests of memory for short lists. Crucially, in the present thesis I employed delayed free recall with long lists of 40 words and found that the benefits of grouping previously established within studies of working memory also benefit long term learning. The results also suggest that tests of working memory capacity may instead record the reconstruction of information after episodic encoding has occurred. The ability to generate segmented mnemonic representations may influence long-term learning and long-term learning may be described as a creative process that capitalizes on the structure of the presented material.

7.1 Mnemonics, prediction errors and context drift

The research journey in this thesis began with the story of Simonides and the Method of Loci. As a reminder “There are two kinds of memory....... one natural, the other artificial. The natural memory is that which is engrafted in our minds, born simultaneously with thought. The artificial memory is a memory strengthened or confirmed by training. A good natural memory can be improved by this discipline and persons less well-endowed can have their weak memories improved by the art.” (Yates, 1966, p. 20). In the Art of Memory, Yates (1966) provides detailed descriptions of how best to train the mind for memory, the Method involves generating mnemonic representations of words, images and locations including recommendations that a) the locations should be distinct, b) there should not be too many ‘intercolumnar spaces’ (i.e., Not too many repetitions of the same boundaries), and c) there should be a definite marker after every fifth item. If the student in the art of memory does not have access to enough real space, then the locations can be imagined, fictional spaces (Yates, 1966). The Method of Loci suggests that to-be remembered information should be transformed into visual-spatial representations and segmented by establishing a ‘marker’ after every fifth item, which is remarkably consistent with current theories of working memory (R.Logie, Camos & Cowan, 2020) and Event Segmentation Theory (Zacks, 2020). The ancient Greeks may have established the original and best form of memory training which could be described in terms of current theories as learning to generate segmented working memory packets. In the current age, fictional spaces are readily available in the form of virtual and augmented reality environments.

The results reported in the present thesis are consistent with Event Segmentation Theory and the proposal of event segmentation as a working memory process that facilitates transfer of information to long-term memory (Richmond, Gold & Zacks, 2017; Radvansky, 2017). Prediction error gating as a process for episodic encoding was explored in the work of McClelland, (1994). When an occurring event does not match expectations a prediction error is experienced which drives memory updating. However, learning can occur in the absence of a prediction error. An alternative to prediction error gating is Hebbian repetition learning (Hebb, 1949). Repeated presentation and recall of to be learned content results in the build-up of a memory trace.

Studies that employ Hebbian repetition learning may be providing only weak event boundaries which require multiple repetitions to promote long-term learning. Providing highly salient or highly unpredictable event boundaries may produce the same long term learning performance as multiple repetition of Hebbian learning. Long-term learning is then driven by adjusting connection weights, unexpected events become less unexpected in subsequent encounters but nevertheless reinforce the initial prediction error trigger for encoding. Learning can occur without an initial prediction error or without multiple repetitions. However, encountering both prediction errors and repetitions may result in longer lasting memories.

The results also lend support to the distinction between fine-grained and coarse-grained event boundaries and further suggest that fine-grained event boundaries may be defined in terms of perceptual saliency or novelty, akin to Gestalt grouping processes (Kohler, 1929). Early examinations of the effect of novelty on memory were conducted by Von Restorff (1933). When presenting a list of stimuli any item that 'stands out' relative to its neighbours is more likely to be remembered. For example, presenting a single number within list of words or presenting a single word within a list of numbers. Importantly, the items presented on either side of the isolated item are not more likely to be remembered. An interpretation of Event Segmentation Theory would predict that event boundaries are defined by prediction errors and items close to event boundaries are more likely to be remembered (Zacks, 2020). If we think of our own lives, some of our strongest memories may be of events that were novel or surprising. Rather than provoking a prediction error, surprise is in effect a detection of change and event boundaries may also be defined in terms of surprise. However, surprising event boundaries defined by detecting change may have a different influence on memory than unpredictable event boundaries defined by prediction errors.

A recent study on the influence of surprise on memory performance provided evidence in support of the view that surprise may also provide a form of event boundary that packets ongoing experiences (Ben-Yakov, 2021). The study employed stop-motion films to present narrative sequences of everyday actions. Events within the sequence could be replaced with a surprise. For example, an event sequence that contains a scene of an individual brushing their teeth with a toothbrush or an identical event sequence that instead contains a scene of an individual brushing their teeth with rhubarb. The results demonstrated an improved memory performance for surprising scenes. However, the study found no memory benefits or deficits for items encountered before or after the surprising scene. An alternative interpretation is that surprise strengthens memory of an item upon an ongoing context drift (Howard *et al*., 2005) but does not provide the effect of a prediction error to encode the preceding elements as an event into long-term memory.

The retrieval of memories may involve the simulation of past events (Schacter *et al*., 2008; Schacter, 2012). Retrieving the basis for simulation can involve skipping between established event boundaries. When asked to scan through packets from a movie from memory, participants reaction times to identify a target item depended upon the number of event boundaries and the distance of the target item to the previous boundary. Event boundaries act as steppingstones for memory retrieval (Michelmann, Hasson & Norman, 2021). If a target item cannot be identified within the currently simulated segment, participants may skip to another event boundary marking the start of a different segment. The time taken to simulate packets and identify target items depends upon a compressed skipping process that does not necessarily match the initial duration of packets. Similarly, previous work has demonstrated that mental simulations of spatial navigation are temporally compressed and depend upon the number of landmarks present along a route (Arnold, Iaria & Ekstrom, 2016).

Landmarks may provide the same effect of event boundaries acting as steppingstones within a movie. The number of landmarks and the distance between landmarks influences the time it takes to mentally simulate the navigation of a route (Kosslyn *et al*., 1978). In addition, previous studies have demonstrated better memory for landmarks that are close to a boundary such as the edge of a map. The effects found for landmarks in studies of navigation are also consistent with Event Segmentation Theory. The studies of navigation suggest that landmarks could be defined as a form of event boundary that acts to segment navigational directions, potentially providing the same benefits found in the present thesis when segmenting word lists with spatial-temporal gaps. Participants may be more likely to become lost if the number of directions to follow between landmarks exceed working memory capacity.

A further phenomenon that could be described in terms of the currently discussed theories are flashbulb memories. Flashbulb memories are so named as an unusually high detailed, long-lasting memory for an unexpected event (Brown & Kulik, 1977). A theoretical account could describe flashbulb memories as benefiting from both prediction error gating and Hebbian repetition learning. The strength of encoding may depend upon the unpredictability of event boundaries. An event may initially provoke and establish a flashbulb memory by providing highly unpredictable event boundaries followed by multiple repetitions during news reports and recall during personal conversations. The 'spike' of initial encoding may depend upon the unpredictability of experienced event boundaries, highly unpredictable event boundaries may provide strong 'one-shot' triggers for episodic encoding.

In addition to saliency and unpredictability, emotional content may also influence the effect of boundaries. Inserting commercial breaks at pre-defined event boundaries within tv episodes has been shown to improve memory performance for the tv episodes (Peterson, Rogers & Bailey 2021). Interestingly, emotionally arousing commercials enhanced the benefits of segmentation by improving memory for temporal order in comparison to emotionally neutral commercials. In another examination of boundaries driven by emotions, participants provided pairs of real-life memories based on factors such as spatial, temporal, and emotional characteristics. Memories defined in terms of emotional content proved to be a better predictor of similar or dissimilar memories than either spatial or temporal factors (Tomita, Barense & Honey, 2021). In addition to differing emotional content, boundaries may also be defined in terms of valence. That is the experience of positive or negative rewards can act as boundaries to segment information. The concept of positive or negative rewards are dependent upon what a participant might expect to see and so are a form of prediction error. However, studies of reinforcement learning have established a distinction between the type of effect positive and negative rewards have on subsequent memory performance and estimates of duration. With positive rewards, participants overestimate time durations whereas with negative rewards, participants underestimate time durations (Toren, Aberg & Paz, 2020).

Rather than distinguishing between a segmentation account and an ongoing context drift, the two theoretical accounts may both be correct. Event boundaries may act as anchor points or steppingstones by creating a gap upon an ongoing context drift. Based on the results reported within the present thesis, fine-grained event boundaries may be defined by salient moments of change and coarse-grained boundaries may be defined by prediction errors. The structure of long-term memory would then depend upon the saliency and unpredictability of boundaries and the number of boundaries experienced. Future work may explore the potential of unifying theoretical accounts.

7.2 Interactions between working memory and episodic memory

Traditional approaches to studying the interactions between working memory and episodic memory in support of long-term learning involved employing Hebbian repetition learning (Hebb, 1961). Repetitions for serial recall of the same number sequence over multiple trials leads to the build-up of an episodic trace. An alternative account suggests that long-term learning may depend upon a process of prediction error gating (McClelland, 1994, 2006). However, as reported in the present thesis, Hebbian learning may simply be a result of multiple repetitions of weak event boundaries defined by moments of change. When participants are aware of repetitions and changes between arrays, learning improves, but learning is very slow if participants do not become aware of the repetition (R. Logie, Brockmole, & Vandenbroucke, 2009; Shimi & R. Logie, 2019). Likewise, learning performance is slower for arrays with more than four items (Shimi & Logie, 2019).

The capacity of working memory has been defined in terms of three-five items or chunks of domain general information (Cowan, 2001, 2010). The results in the present thesis are consistent with this definition however I would suggest that there is not a hard slot limit, but rather an unreliable limit with an increasing probability of losing items furthest from boundaries as list lengths increase. When presenting five highly imageable words between boundaries there are no differences between boundary and non-boundary items. However, when presenting five words of low imageability between boundaries there are significant difference between boundary and non-boundary items. The unreliable capacity of working memory may also depend on domain specific capacities, consistent with Dual-Coding accounts (Paivio, 1971) and multiple domain specific components (Baddeley, Hitch & Allen, 2019, 2020). Presenting information that enables associations between phonological and visuo-spatial information enhances long-term learning as suggested in studies of visuo-spatial bootstrapping (Darling *et al*., 2014) and theories of multimedia learning (Mayer, 2005). The Experiments reported in the present thesis employed long lists and delayed recall and the reported results are consistent with previously established findings of working memory capacities, with peak benefits for four-word packets. Tests of working memory capacity tend to involve short lists with unpredictable endings (Cowan, 2010) and immediate recall. Tests of working memory capacity may record the reconstruction of information after episodic encoding has occurred.

As a further definition, working memory capacity may be described as having an unreliable limit, with an increasing probability of losing items as list lengths increase (Newell, 1972). An unreliable limit could be described in terms of increasing noise in neural activity (Bays, 2015) with working memory as a continuous resource. In a study examining memory for object locations, recall variability increased monotonically from one to eight items (Schneegans & Bays, 2016). The response latency, that is the time it takes for a participant to respond also increased monotonically from one-to eight items. Performance on working memory tests may gradually decrease with continuously increasing loads. However, evidence in favour of slots or a continuous limit may depend on the type of stimulus and the experimental measures. If we test for slots, we may find evidence for slots and if we test for a continuous limit, we may find evidence for a continuous limit. The present thesis employed word lists, as such we may expect to define memory capacities in terms of a slot limit defined by the number of items. Long-term memory performance for the proportion of words recalled improves when presenting segmented four-word packets. Differences in boundary and non-boundary item do not appear until exceeding eight-word packets. Although the use of word lists provides discrete items, the present results could also be explained in terms of a continuous unreliable limit.

The ability to produce and remember sequences may depend on recursively nested structures that may be found in language with phrases embedded within phrases (Chomsky, 1957). While working memory capacity has previously been defined as seven plus or minus two (Miller, 1956) or four items (Cowan, 2010), capacity could be described in terms of chunks or as a data compression process. Rather than being encoded as informational content dependent on slots or increasing noise, the contents of working memory may be encoded in terms of complexity of change (Planton *et al.,* 2021). When employing a sequence violation paradigm, memory performance was predicted by a measure of complexity, defined in terms of the shortest formula required to describe the sequence. Encoding sequences of informational content may rely on a form of compression and nested structures. The study presented simple binary sequences consisting of the letters A and B which could be described in terms of a language of thought. For example, the sequence AABAAB is two repetitions of two repetitions with one change. In a habituation phase participant were presented with sequences of letters and in the test phase participants were presented with sequences that were either the same or had a single letter changed. Participants were required to identify any changes in the previously presented sequences. The ability to detect change depended upon the complexity of the sequence. Human memory could be defined in terms of the ability to recognise repetitions and detect change. Episodic encoding may be defined as a data compression process. The results of the present thesis suggest that even memory tests employing short lists and immediate recall may be tests of episodic recall. As such tests of working memory capacity and evidence in favour of slots or a continuous capacity may depend on the complexity of the initial sequence which influences the efficiency of the compression process.

It is important to note that studies in the present thesis employed delayed free recall and found that when the number of words presented between boundaries could be maintained within working memory, participants were to some extent spontaneously remembering the words in the order of presentation. Memory performance in terms of proportion of words recalled started to suffer after exceeding 4 words between event boundaries. However, differences in performance between boundary and non-boundary words and significant drops in temporal contiguity did not appear until reaching ten or more words between boundaries. The results suggest that participants may start to lose items furthest from event boundaries when exceeding a working memory capacity of four items. Significant differences in temporal contiguity only appeared when comparing conditions that were above and below ten items, suggesting that participants were still to some extent able to generate items in the temporal order of presentation despite a drop in memory performance for the proportion of words recalled. One account of serial order is that of chaining, where remembering each item depends upon remembering the previously presented item. Memory for temporal order should be disrupted as soon as participants are unable to generate some list items as losing item five would impair the ability to generate item six. Memory for temporal order cannot therefore solely rely on chaining successive items, however chaining may be one potential strategy supporting memory for temporal order.

In addition to the importance of segmenting for a capacity limited working memory, the current research suggests that the availability of both phonological and visual-spatial information provides important support for long-term learning. The ability to generate missing information may improve long-term memory performance. The theoretical accounts I propose offers an interpretation of established findings such as synaesthesia. Synaesthesia is a neurological condition in which additional senses are triggered upon experiencing a particular stimulus. The senses are linked so that someone with the condition will, for example, automatically experience seeing colours when presented with numbers or words. An original, famous case demonstrating an extreme form of synaesthesia comes from studies of a man called Shereshevkii or 'S' (Luria, 1987). S was remarkable in that he seemingly could remember everything with which he was presented. Given increasingly long lists of numbers or words or nonsense syllables S did not forget anything: fifteen years after an initial test, S could still recall the original strings of numbers flawlessly. Studies of S suggested that he had at a minimum, six forms of synaesthesia and would experience extremely vivid visual imagery in addition to tastes and sounds and sensations of touch with stimuli that are not normally associated. For example, tasting sounds, hearing shapes or having particular imagery of a person associated with a number, "1 is a proud, well-built man". In the case of S, multiple forms of synaesthesia resulted in the ability to remember everything, however this is described as a torturous experience. S spent most of their life trying to discover a means of forgetting, because it became increasingly difficult to focus on the small amount of information required for ongoing everyday tasks. For S, the inability to simulate and discard events was detrimental rather than beneficial, improving memory performance may not always be desirable, and forgetting may serve an important role in avoiding memory becoming too cluttered with trivial details.

More recent studies of the condition have demonstrated that synaesthesia results in an enhanced memory, however the enhancement only occurs in specific conditions that are relevant to the type of synaesthesia that a person has (Rothen, Meier & Ward, 2012). For example, the automatic association of colours with words (grapheme-colour synaesthesia) leads to an improved memory for the words. Radvansky *et al*. (2011) conducted studies of grapheme-colour synaesthetes, where the semantic and perceptual nature of the stimuli were varied. The synaesthetes outperformed controls in every condition, although the synaesthetes did also show a reduced performance when words were presented in a colour that did not match their synaesthesia. In contrast, the same form of synaesthesia does not result in an improvement in digit span (Rothen & Meier, 2010). In the case of S, numbers had distinct people associated with them, 7 was a man with a moustache, 8 was a very stout woman, 87 was a fat woman and a man with a moustache. In effect an enhanced memory performance could be described as automatically chunking the numbers by associating them with visual imagery and semantic knowledge and imposing a spatial structure (woman on the left, man on the right).

Synaesthesia tends to be defined by a genetic component as it runs in families, by structural and functional distinctions within the brain and is usually present in early childhood. However, many synaesthetic experiences involve learned knowledge such as language which might suggest that pre-existing brain structures in certain individuals allows for a more efficient linking and transforming of one type of information into another and can lead to the automatic experiences of synaesthesia. How much of the experience can be learned? Rothen & Meier (2014) reviewed the evidence on the learned components of synaesthesia and concluded that synaesthesia can be learned, resulting in improved memory performance. To demonstrate the effectiveness of training in synaesthesia, the trainee must consistently and automatically experience the associations of the senses, going beyond the effortful use of mnemonic techniques. As a theoretical interpretation, individuals with synaesthesia may be described as benefitting from the automatic generation of segmented mnemonic representations and a potential approach to working memory training may be to present learning content as a simulation of a synaesthetic experience.

The studies of the present thesis were not primarily aimed at distinguishing between theories of working memory. However, the results support the view of working memory as a separate scene construction system with adaptive constructive processes that can simulate and encode or discard events. Remembering is an imaginative construction (Bartlett, 1932). The results contrast with unitary models, such as embedded processes describing working memory as purely activated long-term memory (Cowan, 2004). While access to long-term stored knowledge is required, working memory may generate simulations that can be discarded if no event boundaries are experienced. However, if event boundaries are experienced, then temporally synchronous representations maintained within working memory may be encoded as new event memories. The results of the present thesis suggest that event boundaries may exist at both a fine and coarse grain and could be defined in terms of variability of salience and unpredictability. Taken together with other work, event boundaries may also be defined in terms of valence (Toren, Aberg & Paz, 2020). The segmentation of working memory event simulations offers an alternative theoretical account to the processes involved in efficient long-term learning.

7.3 Future directions

The current research provides a strong basis to build cognitive theories upon the segmentation of working memory packets, however there are potential limitations. Event Segmentation Theory seeks to describe how the continuous flow of information encountered throughout life may be encoded as quantised episodes based upon the experience of prediction errors (Zacks, 2020). Alternative accounts may be found in the Temporal Context Model (Howard & Kahana, 2001) and in models of sequence learning (Hartley, Hurlstone & Hitch, 2016) which do not require the presence of prediction errors to account for long-term learning. The current study presented random words in random locations upon a four-by-four grid within a sequence of virtual rooms. While the present experiments focused on memory for the presented words a more complete account of memory could also include an exploration of memory for sequential locations both for the grid within a room and for the sequence of rooms containing the grids.

One potential limitation of the current research is that each experiment only made use of random word lists. A more complete account may include studies of memory for images, locations, scenes, and narrative. The encoding of episodes may depend upon either context drift or prediction errors. However, one possible means of reconciling the alternative accounts is to explore the possibility of event boundaries creating gaps upon an ongoing context drift. I would predict that the gaps would be experienced as more time passing than the number of recorded seconds. The event sequencing virtual environment created for the present thesis was designed to be flexible and could be used to run online experiments for investigating the learning of any type of sequential content. Rather than focusing on aspects of a particular task such as recall for words, unifying the principles of context drift and segmentation of working memory simulations may provide a theoretical foundation for explaining a wider range of psychological phenomenon. For example, the ability to reconstruct sequences of navigational directions (Dudchenko, 2010) sequences of human faces (Frowd, Bruce, Burton & Hancock, 1998, Bruce, 2008) or musical passages (Quinn & Watt, 2006). The virtual environment could also be combined with neuroimaging methods to explore patterns of brain activity that may be time-locked to event boundaries (Zacks et al., 2001). The same principles of segmented sequence learning identified in the present thesis may also provide a theoretical account for the learning of any type of content. If change does not occur, then an ongoing context drift is not segmented and a working memory simulation of to-be learned information may be discarded without being encoded into long-term memory.

Recent work has proposed that sequence learning depends upon a language of thought and nested structures (Planton *et al*., 2021). Can human memory be defined as a record of change within nested event sequences? The results of the present thesis suggests that efficient learning depends upon the ability to segment a flow of information into event sequences. Current cognitive theories propose that the presence of event boundaries for the segmentation of sequenced content is crucial for efficient learning to occur. Event boundaries may be defined by prediction errors. However, the present results suggest that sequence learning may also depend on detecting change and temporal clustering within an ongoing temporal context drift. I would question to what extent memory performance may be influenced by imposing fine-grained and coarse-grained event boundaries defined by predictable moments of change or prediction errors at multiple nested levels. Furthermore, working memory capacity may be defined in terms of generated scenes segmented by salient moments of change. Rather than seeking to distinguish between accounts of segmentation and context drift, event boundaries may act as anchor points by creating a gap upon an ongoing context drift. The structure of event memory would then depend upon temporal synchronicity within an event delineated by event boundaries. Memory for the temporal order and temporal duration would depend on the saliency and unpredictability of event boundaries. Future research could aim to develop a more comprehensive unified theory of sequence learning by establishing the contributions of an ongoing temporal context drift and the presence of fine and coarse-grained event boundaries within nested event sequences.

The research of the current thesis employed a custom-built event-sequencing virtual environment consisting of multiple rooms. The environment provided a fine detailed level of control for distinguishing between fine-and coarse-grained event boundaries and a temporal context drift. Travelling between locations within a virtual environment imposes event boundaries and provides temporal clustering that aids in the segmentation and clustering of information and results in an improvement in long-term memory performance (M. Logie & Donaldson, 2021). The improvement can be found in the quantity of information recalled, the clustering of the information by the location of presentation and the temporal order of the presented information. Crucially, prediction errors driven by the presence of doorways was found to disrupt memory for temporal order. Improvements in memory for temporal order were found when employing predictable event boundaries defined by spatial-temporal gaps between locations within the virtual environment.

Current established theories propose that the segmentation of long-term memory and memory for temporal order are dependent on prediction errors, however the present work outlines how long-term memory performance and memory for temporal order may be improved with predictable moments of change. Outstanding questions remain as to the contributions that predictable, unpredictable event boundaries and an ongoing temporal context drift have on the structure of memory and the experience of time. The questions identified in the present thesis may serve as the basis for the future work outlined below. There is an ever-increasing need for learning content. Building on work identifying the cognitive processes that support long term learning can provide a framework for creating efficient means of presenting learning content that is grounded in cognitive theory. The research reported in the present thesis made use of an innovative virtual learning environment and determined that memory performance may be improved be presenting segmented working memory packets within a virtual environment (M. Logie & Donaldson, 2021). The virtual environment allows for fine detailed control over experimental conditions with potential to aid in developing a general theory of long-term learning that is based upon the presence of event boundaries, a context drift signal and segmented sequence learning. The environment may also be adapted as prototype presentation software to demonstrate the benefits of presenting learning content as segmented sequences of working memory packets within virtual environments.

One prediction based on the present findings is that event boundaries may exist upon a sliding scale of salience, from expected to unexpected, and act as triggers for episodic encoding. Mnemonic representations that are temporally synchronous within working memory may be encoded into a new event memory upon experiencing an event boundary, the less salient a boundary the more repetition may be required for long-term learning to occur. Providing boundaries of low salience along with multiple repetitions may provide the same long-term memory performance as presenting boundaries of high salience with few repetitions. Is one shot learning dependent on event boundaries defined by saliency of change? The ability to provide efficient one-shot learning will greatly benefit rates of learning.

The present work identified memory improvements when segmenting word lists with spatial-temporal gaps, but also with temporal gaps only. The effectiveness of an event boundary may be defined more generally as a moment of change that provokes the need for resources that are distinct from recently encountered information. While the importance of landmarks for spatial cognition is well established, landmarks may be defined as a subset of event boundaries, because landmarks provide salient moments of change. Segmenting sequentially presented navigational routes should also provide an improved memory performance for the routes. Spatial-temporal information may provide boundaries for segmenting word lists. Word lists may provide boundaries for segmenting spatial-temporal information. Landmarks may be defined as a subset of event boundaries based on what a participant may expect to see within an environment. Establishing the generalisability of event boundaries at both fine and coarse grains would suggest that long-term memory performance for any content may depend on segmented sequence learning.

Working memory may be reconstructive in nature. Mnemonic representations maintained within working memory may be initially generated based on information available from both perception and long-term memory. Establishing a working memory representation may depend on the reinstatement of boundaries delineating an event memory. Upon remembering, the size of the gap between boundaries and the density of information between boundaries may indicate that more information was initially presented than is subsequently available. Would the occurrence of false alarms in tests of recognition vary depending on the size of the gap and the density of information presented between boundaries? Identifying a means of minimizing false memories will aid learning by reducing misunderstandings and the potential need to unlearn falsehoods.

Current theories of sequence learning propose an ongoing temporal context drift, however, memory for temporal order may be manipulated by imposing fine and coarse-grained event boundaries defined by salient moments of change or prediction errors. Event boundaries may mark anchor points upon an ongoing temporal context drift. The structure of event memory then depends on temporal synchronicity within an event delineated by event boundaries. Are event boundaries experienced as a temporal gap even when no additional time passes and does the size of the temporal gap depend on the saliency or unpredictability of change?

7.4 Conclusion

The findings reported in the present thesis using a custom and flexible virtual learning environment, shows that long-term learning can be improved by providing spatial-temporal gaps between to-be learned content. Future work may build on the current research which showed that employing spatial-temporal gaps to segment word groups that can be maintained within working memory results in an increase in the quantity of information that can be remembered. An increase in clustering of the remembered information by the locations of original presentation and an increase in remembering the information in the order of presentation. The present results were interpreted as suggesting that prediction errors, proposed by Event Segmentation Theory, and driven by the presence of doorways, may have a specific effect of disrupting memory for temporal order. The experience of an event boundary can create a temporal gap within memory, even if no additional time passes. Memory improvement effects, memory for temporal order and increases in clustering can be driven by predictable rhythms of spatial-temporal gaps, however spatial-temporal gaps may simply be an effective means of providing moments of change that exist on a continuum of saliency. Rather than prediction errors, it was suggested that fine-grained segmentation may depend on detecting a salient moment of change as and when the moment occurs.

Based on the reported results, I propose the existence of a ‘goldilocks zone’ for episodic encoding, delineated by event boundaries, that can generate distinct mnemonic representations, composed of phonological, visual, spatial and semantic information. If working memory is filled to capacity in one dimension between boundaries, capacity remains for other dimensions to be filled. Over or under- loading working memory between event boundaries may result in an impaired long-term memory performance. Working memory may be described as a scene construction system for the simulation of events. If event boundaries defined by a variable rate of change are not experienced, then information may not be encoded into long-term episodic memory. Segmenting learning content with highly salient event boundaries may support one shot episodic encoding without the need for repetition.

The results of the present thesis suggest that event boundaries act as triggers to encode mnemonic representations maintained within working memory into longer-term storage, presenting segmented working memory packets may optimise long-term learning. Further, the segmentation of events appears to be driven by the presence of expected boundaries, with episodic memory encoding gated by experiencing moments of change provided by predictable spatial-temporal gaps. Future research may be able to identify an optimal tempo for the segmentation of events dependent on the presented rhythm and saliency of event boundaries. Presenting events that map onto an individual's rhythms may allow for more efficient formation of memories and a means of improving long-term learning. An additional potential approach may be to employ virtual reality environments to both establish and reinstate experienced events and provide highly salient, novel event boundaries to provide more efficient learning content or to aid individuals whose segmentation ability may be improved.

Future research may further explore the segmentation of events, by treating spatial-temporal gaps and the presence of doorways as fine- and coarse- grained event boundaries and studying the structure of memory by presenting to-be remembered information as a tour through a virtual learning environment. The virtual learning environment used in the present thesis provides a strong experimental tool that may also provide the basis for presenting learning content as segmented working memory packets. The use of virtual learning environments provides a fruitful approach to studying interactions between working memory and episodic memory as well as an effective means of providing learning content that is grounded within cognitive theory. Developing a virtual learning environment to pre-define complex event sequences along with the saliency and predictability of event boundaries and the density of information present between boundaries provides a powerful tool that may be employed in studies of the structure of memory with implications for improving life-long learning. The structure of episodic memory may depend on event boundaries acting as anchor points by creating gaps upon an ongoing context drift. Boundaries may occur at both a fine and coarse grain. Human memory may be defined in terms of change complexity within nested event sequences composed of segmented working memory packets.

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