Do Doorways Really Matter: Investigating Memory Benefits of Event Segmentation in a Virtual Learning Environment

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Abstract

Event segmentation allows the flow of information experienced in life to be partitioned into distinct episodes, facilitating understanding of the world, action within it, and the ability to store information in memory. One basis on which experiences are segmented is the presence of physical boundaries, such as walking through doorways. Previous findings have shown that event segmentation has a significant influence on memory, with better memory for events occurring within a single boundary (compared to events that cross boundaries). By manipulating the features of boundaries and the amount of information presented between boundaries the present research investigates the nature of event boundaries. We make use of a virtual learning environment to present lists of words in virtual rooms, testing memory for the word lists as a function of the presence or absence of spatial-temporal gaps and physical boundaries during encoding (i.e., by maintaining participants within individual rooms or moving them through doorways between rooms). Across four experiments, we show that segmenting information with spatial-temporal gaps results in an increase in clustering (reflecting the structure imposed at encoding) an increase in the number of words remembered during later tests of episodic recall (a memory benefit) and an increase in recalling the words in the order of presentation. Importantly, however, the data show that the presence of doorways is not required for event segmentation to benefit memory: increases in clustering, memory for temporal order and recall performance were found with temporal gaps alone. Furthermore, the results suggest that episodic memory may be optimised if the amount of information between boundaries can be maintained within working memory. We discuss the implications of the findings for Event Segmentation Theory and propose an alternative account of the episodic memory benefits based on temporal clustering.

Keywords: Event Segmentation; Working memory; Episodic memory; Virtual environment; Memory training.

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 paper 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 of a scene (i.e., in the middle of an activity) resulted in no drop in performance 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 exist 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 1. 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.

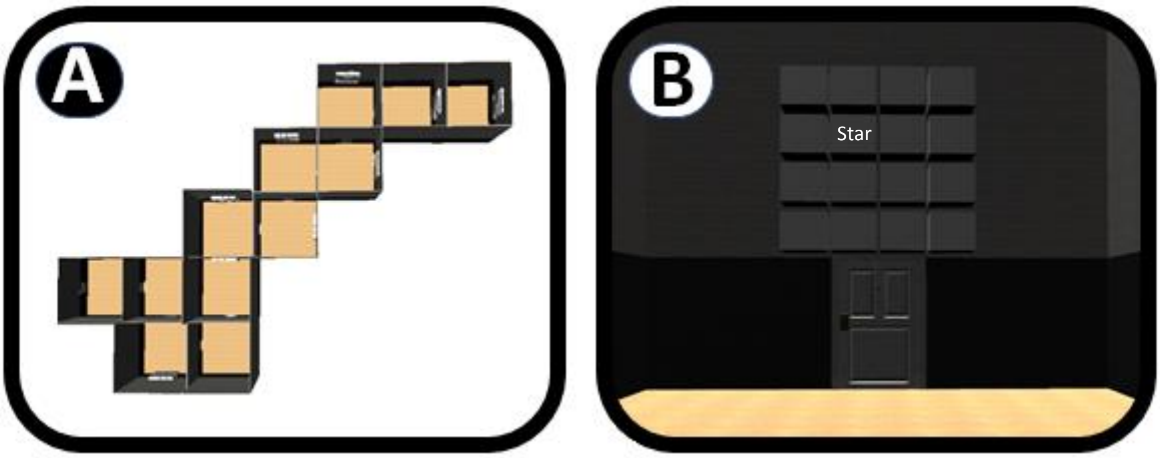

Figure 1: Panel (A) Top down view of the virtual learning environment created in Unity3D. Every room is identical in size, shape, and colour. Movement through the space was automatic, ensuring consistent visual input, with a consistent pace, for all participants. Panel (B) First person view within a 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.

1. 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 1, 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.

1.1. Methods

1.1.1. 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.

1.1.2. Materials

The experiment involved a virtual environment presented on a laptop computer (illustrated in Figure 1), 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 1 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. Future studies can manipulate and draw direct comparisons with the current study not only for the quantity of information between boundaries but also the presence of phonological, visual and spatial information as proposed by the multiple components theory of working memory (Baddeley, 1986, 2000, 2007; Baddeley & Hitch, 1974; Baddeley et al., 2021; R Logie, 1995; 2011; R Logie et al., 2021). Allowing for a 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.

1.1.3. Procedure

1.1.3.1. 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.

1.1.3.2. 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, that they would again be presented with a series of words within the virtual environment and asked to remember as many words as possible.

1.1.3.3. 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.

3.1. 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 2(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 2(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.

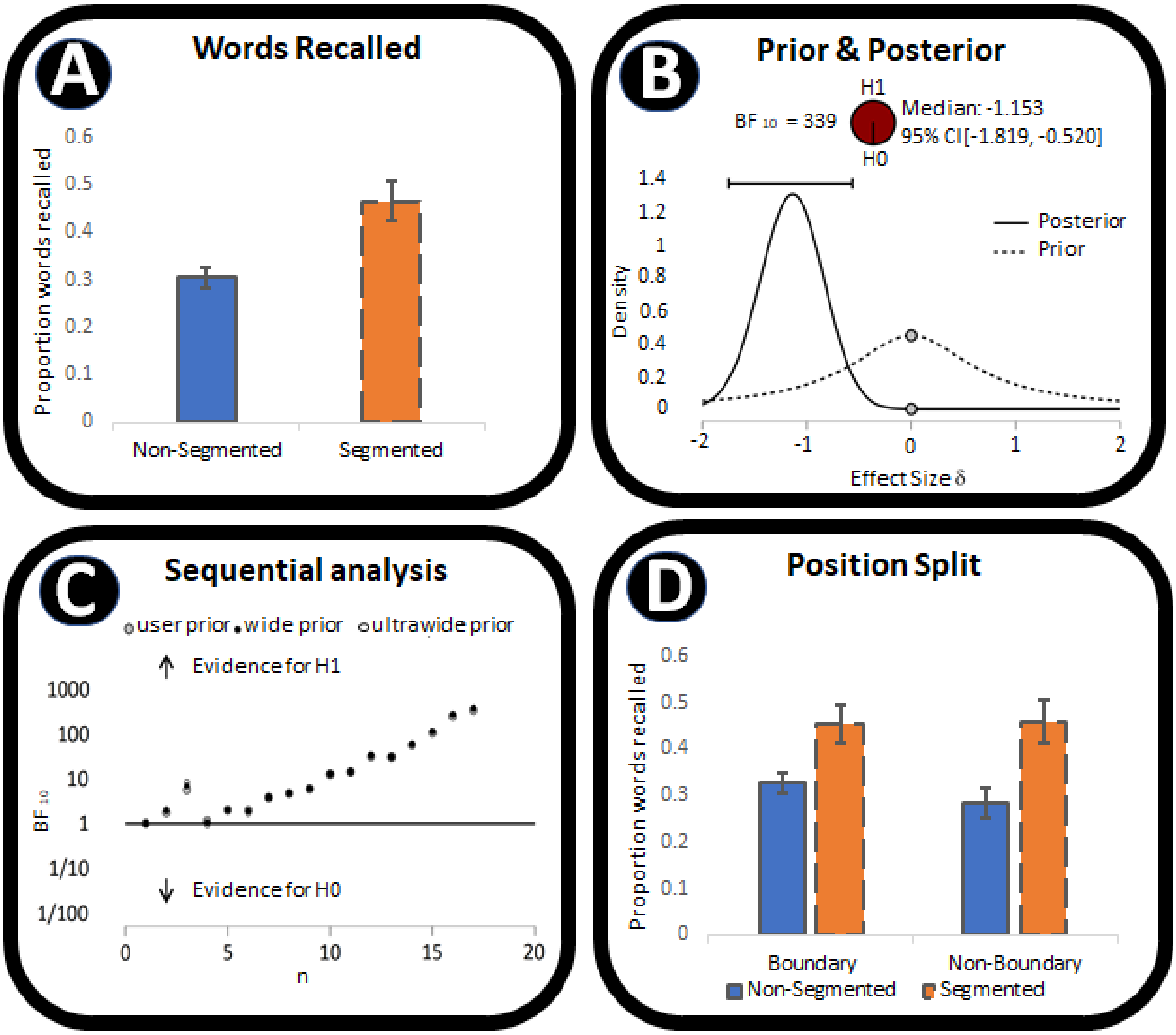

Figure 2, Panel A: Proportion of words recalled following non-segmented (40 words in 1 room) versus segmented (4 words per room across 10 rooms) learning, showing a clear effect on memory. Error bars represent ± 1 standard error of the mean. Panel B: Bayesian paired sample t-test results for Experiment 1, 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. 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.

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 2(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 2(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 an interaction. 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.

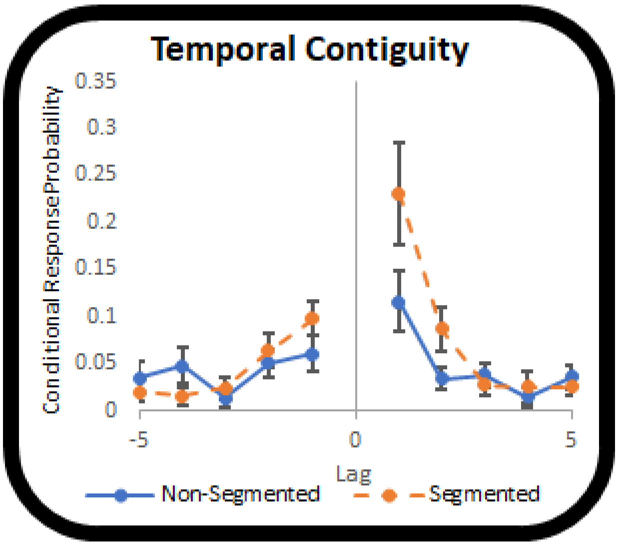

Fig 3: Conditional Response Probability (CRP) as a function of lag. Participants show no significant change in lag+1. Error bars represent ± 1 standard error of the mean.

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 3, 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 does not result in an increase in recalling the words in the order of presentation.

3.3. 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 retrained). 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.

4. 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.

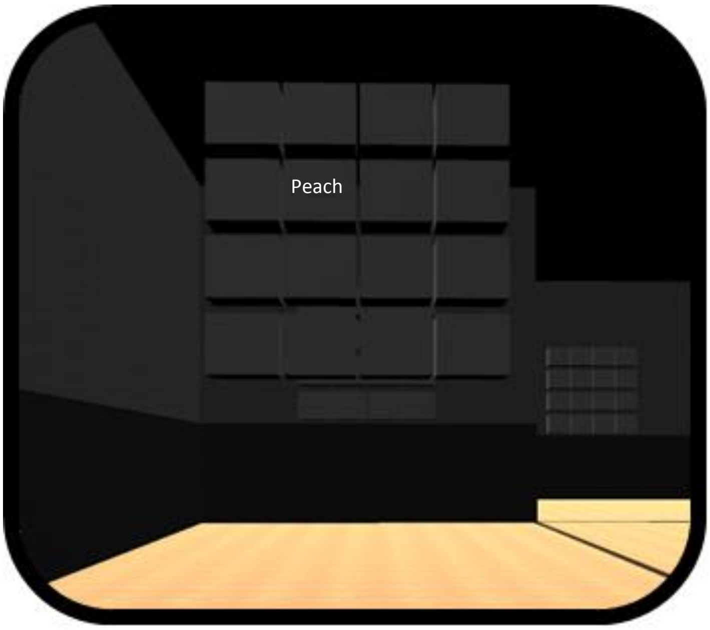

Figure 4: Sample view of the alteration to the virtual learning environment used in Experiment 2, with no physical boundary provided by walls or doorways between locations. Boundaries include crossing a line on the ground, passing beneath the grid, and turning corners.

4.1. Methods

4.1.1. 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.

4.1.2. Materials

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

4.1.3. 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.

4.1.4. Statistical analysis

The analysis used the same measures as in Experiment 1.

4.2 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.

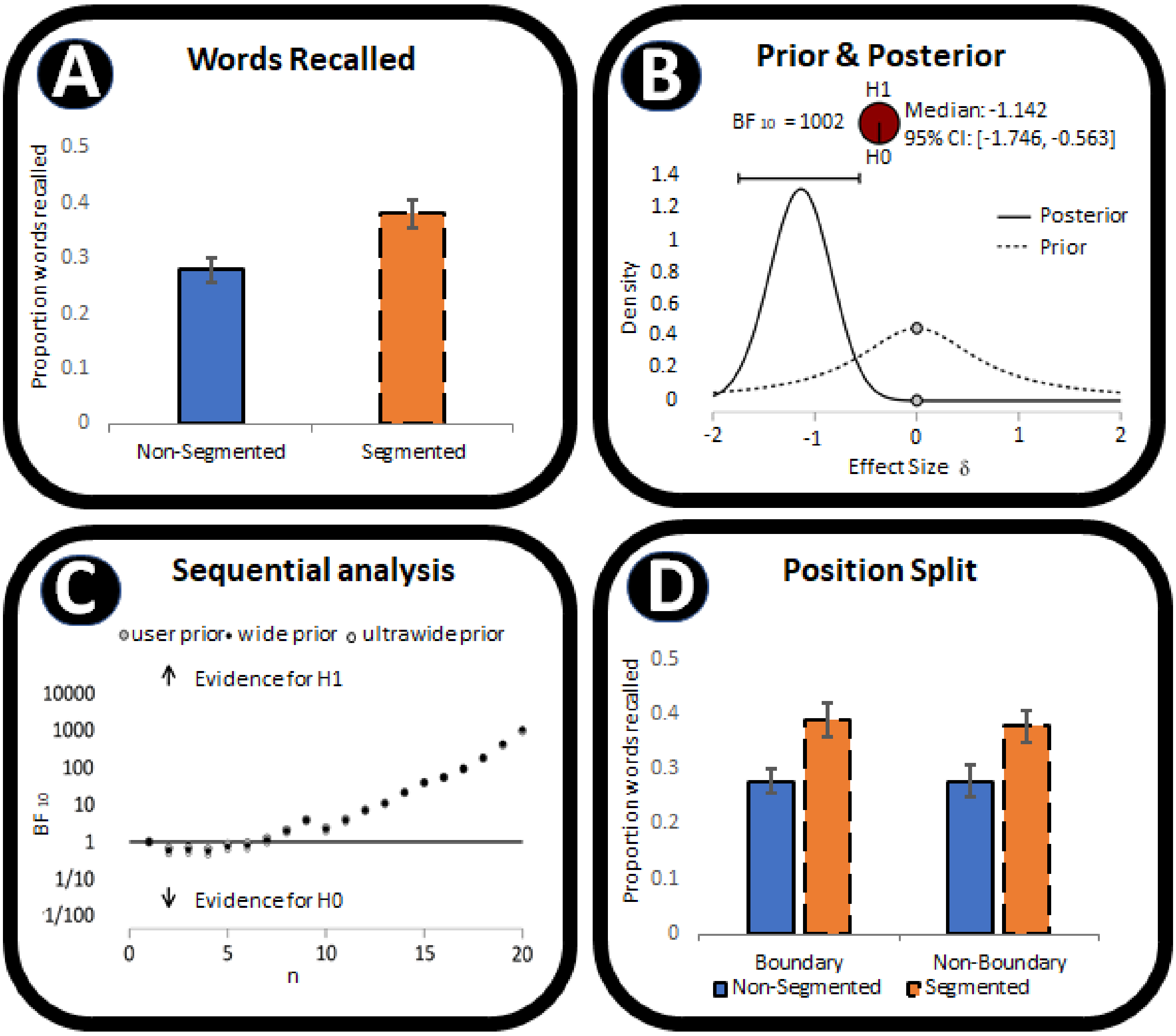

Figure 5, Panel A. Proportion of words recalled for non-segmented (40 words in 1 room) versus segmented (4 words per room across 10 rooms). Panel B: Plot of prior and posterior for experiment 2. Panel C: Bayesian sequential analysis. Panel D: Memory improvement is not specific to items closest to boundaries.

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 5(C) displays 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 5(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.

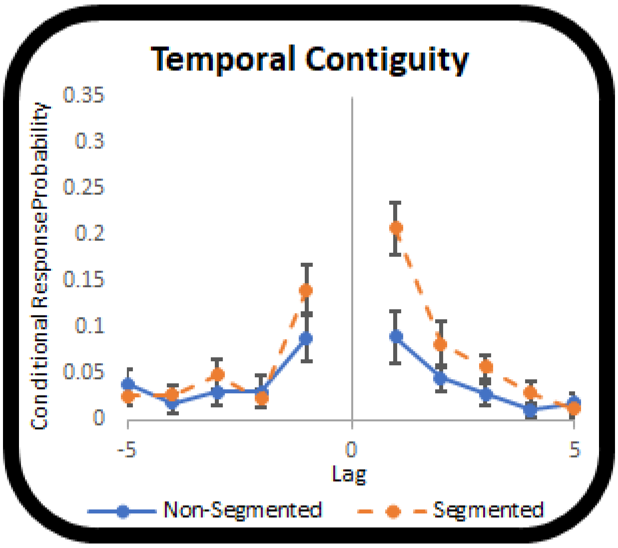

Fig 6: Conditional Response Probability (CRP) as a function of lag. Participants show moderate evidence for an increase in lag+1.

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 6, 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.

4.2. 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 although rich contextual details are not required to find an effect. 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. The segmentation of events may not be due only to the prediction errors of 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 are no doorways, participants are better able to predict what will 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. 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.

5.1. Methods

5.1.1. 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, course credit was provided for participation. All participants gave informed consent. Ethical approval was obtained from the University of Stirling general university ethics panel.

5.1.2. 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.

5.1.3. Procedure

5.1.3.1. 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.

5.1.3.2. Test phase

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

5.2. 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.

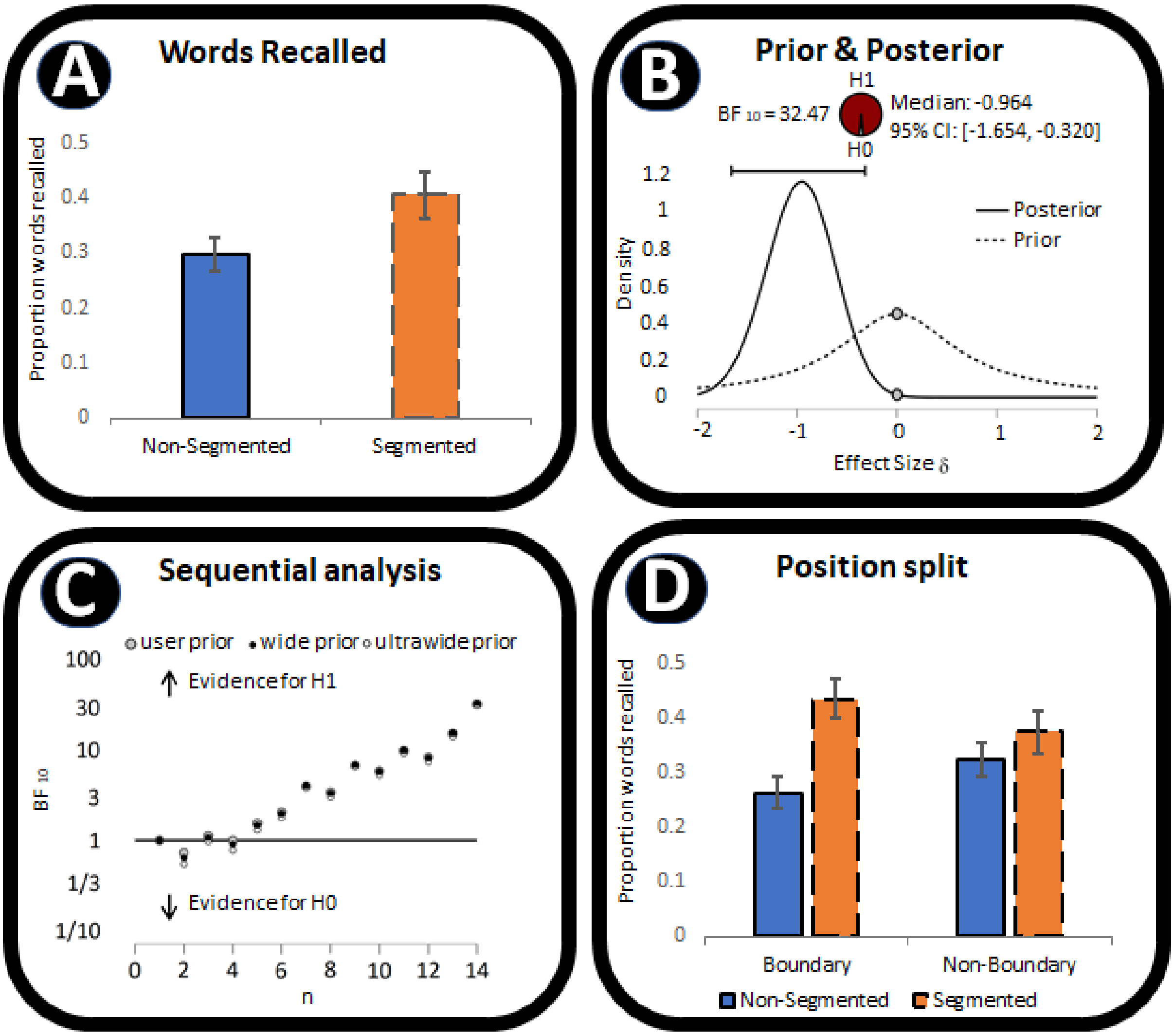

Figure 7, Panel A. Proportion of words recalled for non-segmented (40 words in 1 room) versus segmented (4 words per room across 10 rooms). Panel B: Plot of prior and posterior for Experiment 3. Panel C: Bayesian sequential analysis. Panel D: Memory improvement for boundary and non-boundary words.

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 7(C) displays 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 7(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.

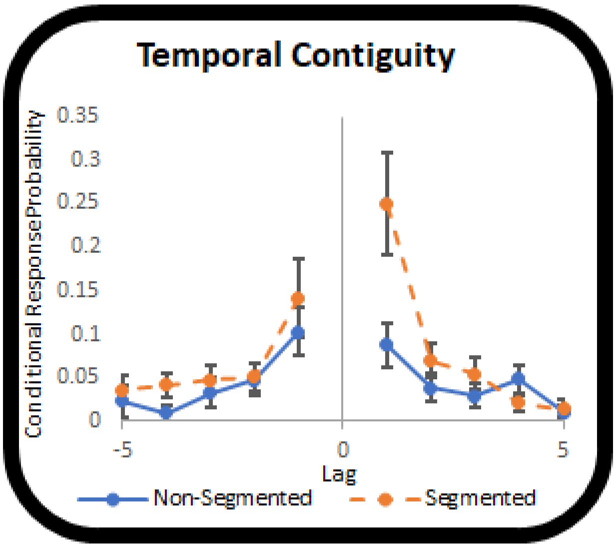

Fig 8: Conditional Response Probability (CRP) as a function of lag. Participants show moderate evidence for an increase in lag+1.

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 8, 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.

5.3. Discussion

The memory improvement effect found in Experiments 1 and 2 remained present 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 rehearsals on long-term learning of multiple lists and found no benefits. In a study by Tulving (1966) participants were presented with word lists, one group of participants was 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, participants were 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. So, 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 interpretation could be that for an event to be encoded, participants need to encounter a boundary which includes ceasing to rehearse to-be remembered items. Maintaining information within working memory could be described as delaying the experience of a boundary. Episodic memory has been proposed 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. But in any case, 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.

6. 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. The 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 vs 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.

6.1. Methods

6.1.1. 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.

6.1.2. 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.

6.2. 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.

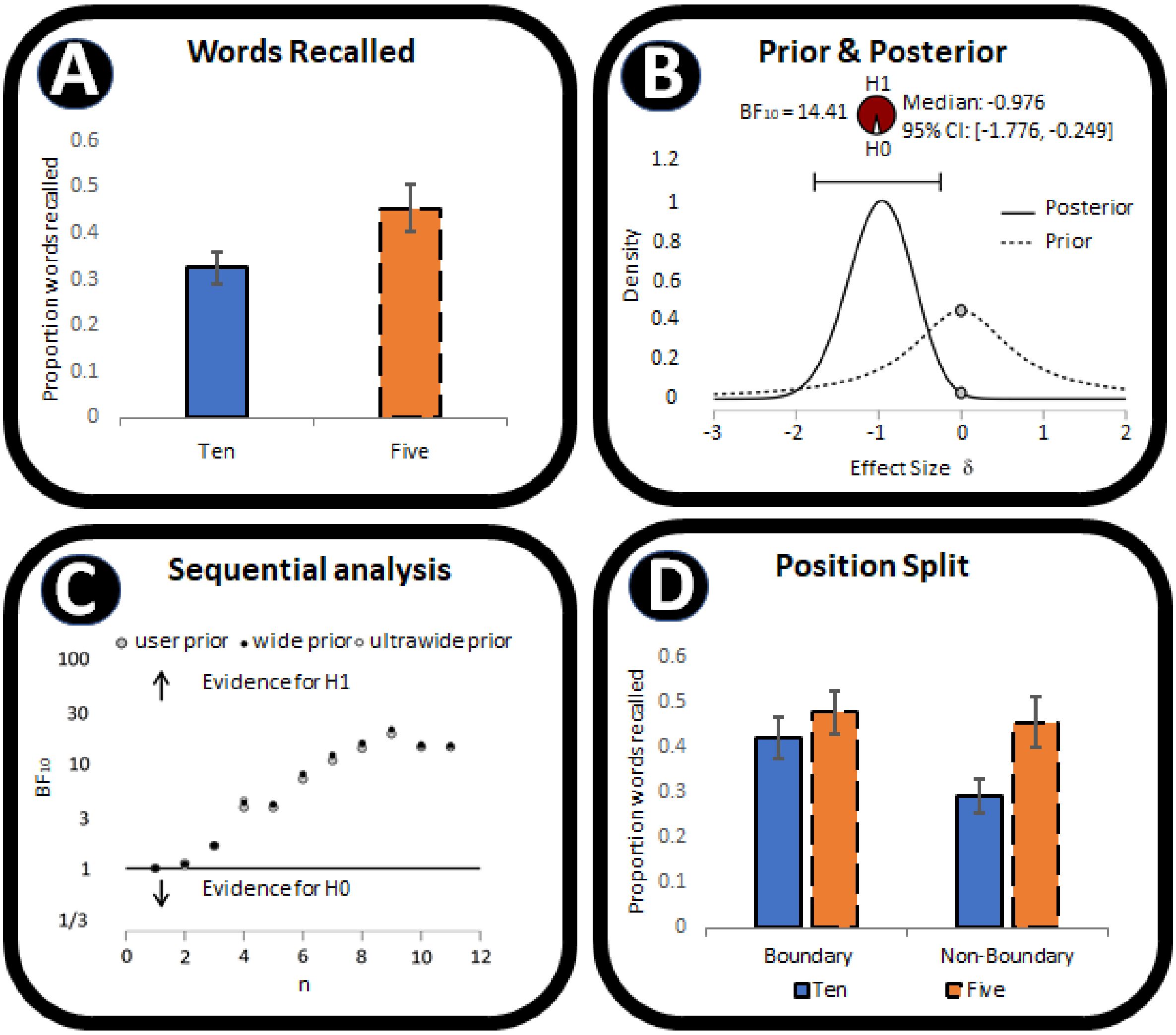

Figure 9, Panel A. Proportion of words recalled for Ten words (10 words per location across 4 locations) versus Five words (5 words per location across 8 locations). Panel B: Plot of prior and posterior for experiment 3. Panel C: Bayesian sequential analysis. Panel D: Memory improvement effect due to 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 9(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 and third and fourth words presented at each location). Figure 9(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 $BF_{incl} = 47.44$, 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 9, 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.

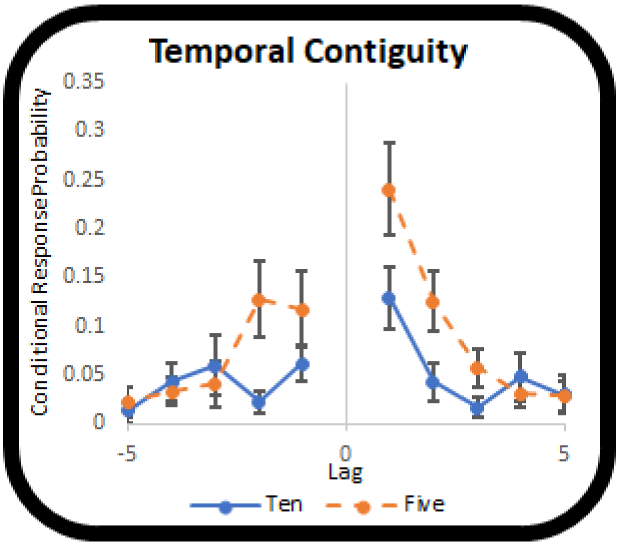

Fig 10: Conditional Response Probability (CRP) as a function of lag. Participants show anecdotal evidence for an increase in lag+1.

Analysis of CRP revealed that there was no significant difference in Lag+1 between the non-segmented condition (M = 0.13; SD = 0.11) and the segmented condition (M = 0.24; SD = 0.16). As shown in Figure 10, 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.

6.3. 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 9, 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 such 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.

7. 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 for creating 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 showed 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. 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. So, 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 memory improvement effects. 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. 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 be experienced as a temporal gap even if there is no difference in the amount of time passing. 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 upon detection of a salient moment of change.

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.

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 segments 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 however, 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. 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. Whereas items appearing further apart in time are separated due to a decreased contextual overlap (Howard & Kahana, 2002). Hartley, Hurlstone & Hitch (2016) 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. The 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, 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, but also highlight that temporal clustering also provides a 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 rehearsals of the presented words. For example, in a study of mnemonic training one group of participants were specifically instructed to conduct additional rehearsals 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, 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 are important, memory improvement effects can be found without employing the concept of spacetime.

The present research employs a reductionist approach. After finding an effect, components of the experiment are systematically removed. If the effect changes or disappears then we can conclude that the removed component had an important influence on the effect. 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. Although 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. 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 further suggest a possible approach to improving learning by segmenting to-be remembered items with spatial-temporal gaps; 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 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. We may 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. 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. 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 that can include the dimensions of 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. In addition, previous studies have identified a hierarchical event structure with segmentation occurring at both a fine and coarse grain (Kurby & Zacks, 2008). 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 without the presence of doorways may provide a means of optimising memory performance.

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