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The effects of rhythmic presentation of stimuli on item and source memory

A thesis submitted to Middlesex University in partial fulfilment of the
requirements for the degree of MSc by Research

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Abstract

Previous research has shown that presenting stimuli in a temporally consistent manner (i.e. rhythmic or structured timing) during a study task can increase accuracy in a subsequent recognition test, compared to arrhythmic or unstructured presentation timing. However, no research has been done on whether this benefit extends to source memory (i.e., memory of contextual details). In this study, thirty-one participants (mean age = 27.39 years; SD = 4.92), were presented with a stream of images of everyday objects with either a cyan (blue) or magenta (pink) border during a study task. This was then followed by a recognition task where participants were instructed to respond for each item whether it was previously presented with a blue border, previously presented with a pink border, or was new. A blocked design was used, in which half the blocks the images were presented in a rhythmic temporal structure during encoding, and half the blocks were presented in an arrhythmic temporal structure during encoding. Electroencephalogram (EEG) was recorded throughout the experiment to measure the electrical activity in the brain during both the study (encoding) and recognition (retrieval) tasks. This was to understand the underlying neural processes involved in both the encoding and the retrieval of information. Specifically, we were interested in the effect of presentation timing during encoding on a number of memory-specific event related potential (ERP) components that have been observed in previous studies on recognition memory; namely the Dm effect (‘differential neural activity based on memory') at encoding, and the FN400 old/new effect, the late positive component (LPC) old/new effect and Late Frontal Effect (LFE) at retrieval.

Overall, there was no effect of temporal condition on item memory accuracy (i.e., the participants ability to discriminate between previously studied and new items). The two old/new effect ERPs that have been studied in relation to retrieval (the FN400 and LPC old/new effects) were replicated in this study for item memory, whereby items correctly identified as old elicit a more positive amplitude than items correctly identified as new. However, there was no effect of temporal condition on these ERPs. That is, the FN400 and LPC old/new effects were present in both the rhythmic and the arrhythmic conditions. No old/new effects were seen for the Late Frontal Effect (LFE) in either temporal condition. For source memory, no old/new effects were seen for the FN400, LPC or LFE when correct source and incorrect source responses were compared. However, source accuracy in the behavioural data was significantly greater in the arrhythmic than the rhythmic condition (i.e., the participants ability to identify the correct border colour for old items). This suggests that different processes may be used for retrieving source information compared to the processes required for item recognition only.

Introduction

Background on memory research and types of memory

The topic of memory in cognitive neuroscience aims to understand how information is coded and represented in the brain for later retrieval. Memory is an information processing system where information can be processed (encoded), stored, and retrieved. We receive sensory information from the environment via our sense organs. Encoding is the input of that information into the memory system where it is processed so that it can be stored in memory. Storage is the retention of encoded information and retrieval is the act of extracting the information out of storage and into conscious awareness.

A number of models and theories about memory have been proposed over the years. One of the earlier theories was by Atkinson and Schiffrin (1968) who proposed a Multi-Store Model, which suggested that there are three separate memory stores; sensory, short-term, and long-term memory, and that information passes between these stores in a linear fashion. This model proposed that information is first detected by sense organs and stored in sensory memory. When this information is attended to it is stored in short term memory (also known as working memory), and it is from this store that information can be recalled. Information in the short-term memory that is given meaning or rehearsed will move into long term memory. Information can be retrieved from long-term memory back into short-term memory where it can then be recalled. However, this model did not account for information that is rehearsed but still forgotten, or information that is not rehearsed but still able to be remembered.

Craik and Lockhart (1972) proposed the Levels of Processing Model which hypothesised that the deeper the processing the longer the memory trace will last, that is, how the information is initially encoded affects how well it is remembered. Shallow processing involves processing the item's physical or sensory features, such as size, colour, volume etc., whereas deep processing involves creating meaning and semantic analysis such as associations with past experiences or other top down processes. They claimed that deeper processing of information leads to easier recall of that information.

A number of different paradigms can be used to test memory, such as free recall, cued recall and recognition tests. In a free recall test the participant is asked to recall previously studied information, but without any specific cues e.g., the participant is asked to recite a list of previously studied words or objects. Whereas recognition memory is the ability to distinguish between previously encountered and novel items. According to Tulving (1968), recognition memory is generally better than recall due to the overlap of information presented in the recognition test and the information in the memory trace, compared to a recall test where no information is presented. However, they found that participants can sometimes perform better in recall tests than recognition tests if effective retrieval cues are used that provide semantic meaning or coincide with additional information stored about the item to be remembered. Morris et al. (1977) also argued that shallow / non semantic processing is not always inferior to deeper / semantic processing, instead they proposed that it is the overlap between encoding and retrieval processes that enhances performance, in a theory known as Transfer Appropriate Processing (TAP).

Recognition memory

There have also been memory theories and models specifically in relation to recognition memory. For example, the dual-process model of memory which proposed that familiarity and recollection (also known as “remember” or “know”) are two separate, distinct processes. Familiarity is thought to be a faster, automatic response that an item had been seen before but without conscious awareness of the memory experience, whereas recollection is a slower process where specific episodic details of the memory are consciously remembered (Jacoby, 1991; Yonelinas, 2002). In contrast, the single-process model proposed that recognition memory exists along a continuum and the strength of the memory depends on the depth of processing. That is, deeper processing creates a stronger memory signal and recognition decisions at test are based on the strength of that memory signal (Hirshman & Master,1997; Slotnick & Dodson, 2005; Dunn, 2004; Wixted, 2007), similar to the model proposed by Craik and Lockhart (1972).

Recognition memory in humans can be studied via a recognition test paradigm where participants are first presented with a list of items to study, followed by a delay period, then presented with a test. In the test the previously studied items are presented again, along with a number of new (unstudied) items, and participants have to make a judgement whether they have seen that item before, often by a yes/no response or on a scale about their level of confidence in remembering an item. This latter response methodology has also been used by some researchers to attempt to study familiarity versus recollection in the dual-process model (Woroch & Gonsalves, 2010; Thavabalasingam et al., 2016). However, recollection and familiarity are more commonly assessed using the remember/know paradigm (Tulving, 1985; Gardiner & Java, 1993), whereby participants are instructed to respond ‘Remember’ if they consciously remember seeing the item i.e., they can remember the experience of seeing the item in the list. Whereas, if they recognise the item but do not consciously remember the experience of seeing it then they are instructed to respond ‘Know’ (Dűzel et al., 1997). In all these examples the old items presented at test are identical to those presented in the study phase, i.e., the images do not change, or have any additional features added or removed between study and test.

Source memory

Memory for the context in which an item is experienced is known as ‘source memory’. This could be spatial, temporal or a specific contextual feature of the item (Johnson et al., 1993). A real-world example of this could be knowing about a current event or specific fact (e.g., the supermarket opens at 9am on Saturdays) and the source memory is also remembering that you heard that information from a friend (as opposed to reading it online). Source recognition is thought to rely upon recollection-based processing in the dual-process model, and deeper processing in the single-process model (Rugg & Curran, 2007; Wixted, 2007; Yonelinas, 2002). Examples of the different types of source memory include: items and their spatial orientation (Van Petten et al., 2000) or visual presentation (Kuo &Van Petten, 2006; Guo et al., 2006; Ecker et al., 2007), mode of presentation, e.g. visual or auditorial (Goolkasian & Foos, 2002) or words spoken and the voice that spoke them (Senkfor & Van Petten, 1998).

There are also different methodologies that can be used to test source memory in terms of how participants are instructed to respond in the test phase. Cycowicz and Friedman (2003) summarised these as being one of three different experimental paradigms. These are a sequential response, an exclusion response, or a three-button response. The study phase in all three paradigms is identical, that is, participants are required to study a list of items that belong to one of two sources. The test phase is also identical in that a stream of items is presented one at a time to the participant. This stream of items includes previously studied (old) items as well as unstudied (new) items. How these paradigms differ is in terms of how the participants must respond. In the sequential response paradigm, participants must first decide if the item is old or new. Then for items judged as old there is a second decision as to whether the item belonged to source A or source B. For example, in Addante et al. (2011) source memory was assessed by the type of task given to the participant at encoding. In half the encoding blocks, participants had to respond yes or no to whether they thought the item was pleasant (pleasantness task), and in the other half they had to respond yes or no to whether they thought the item was alive (animacy task). At retrieval, participants first had to respond whether the item was old or new. Then for items judged as old participants were subsequently asked to respond whether the item was previously presented in the pleasantness task or the animacy task. Therefore, at each stage a binary decision (i.e., old versus new; or pleasantness versus animacy) is made, each with a 50:50 probability. The drawback to this approach is that it separates item and source judgments when these decisions and retrieval processes could happen simultaneously. This is particularly important when brain activity is measured at the time of test, as in the sequential response methodology the recordings for the source decision response may not coincide with the source judgement. The second type of paradigm used for source memory is the exclusion response paradigm. This was developed by Jacoby (1991), and involves one source as a target (e.g., items in red) and participants are instructed to respond with one button if the items in the test phase were presented in the target source during the study task, and another button for both items that were presented in the other source and for new items. This approach was developed to avoid the drawbacks with a sequential response but to maintain a binary response decision while engaging source memory processes. However, the drawback to the exclusion response methodology is that it does not measure accuracy for item memory, as new items and old items with the non-target source are grouped together under one response. Finally, the three-button response task is where participants are instructed to respond in the test phase via a choice of three buttons; one button for items previously presented in Source A, one button for items previously presented in source B and one button for new items. For example, in a study by Guo et al. (2006) participants were asked to study Chinese words presented on either a square or circular background and in the test phase were required to respond via three-buttons; one for old-circle, one for old-square and one for new. The benefit to this approach is that item and source memory can be measured simultaneously. That is, the accuracy for item memory can be measured from all correct old responses (regardless of source response) and the accuracy for source memory can be measured from correct source responses, without the need for separate response tasks. The corresponding neural activities for these respective trials can also be analysed via the single response task. However, the drawback to this approach is it requires a single trinary decision rather than two binary decisions. Therefore, the challenge is whether the decision probabilities should be equal between old versus new items, e.g., 50% Old (25% Source A, 25% Source B) and 50% New; or instead whether there should be equal probabilities across the three response options, e.g., 33.33% Old-Source A, 33.33% Old-Source B, 33.33% New.

In terms of the three-button source test, there are also differences in previous studies in terms of how the items are presented in the test phase. Old items could be presented with the same or different source information at test and participants have to judge whether the item was old-same source, old-different source or new (Kuo & Van Petten, 2006; Ecker et al., 2007). Alternatively, items could be presented without any source information at test and participants have to judge whether an item was old-belonging to source A, old-belonging to source B, or new (Guo et al., 2006).

Kuo and Van Petten (2006) used the former three-button approach (same/different source decision) to find out if the type of encoding task affected source memory. At encoding participants studied items that were each in a single colour and were asked to make either a size judgement (bigger or smaller than a computer monitor) or a colour congruity judgement (is this colour likely or unlikely for this item). As both judgements required them to think about the item's properties, they hypothesised that item memory should be consistent in both conditions, therefore it would allow them to isolate source memory. They predicted that the colour congruity judgement would lead to greater integration of the colour with the item at encoding and consequently would lead to greater accuracy in source recognition. At test participants were presented with a stream of items that were either old (either in the same colour as the study task or a new colour) or new. They were required to respond to each item via a three-button judgement - old-same colour, old-different colour or new. The results showed that during encoding size judgements were made significantly faster than colour judgements, suggesting the colour judgements required greater consideration and perhaps deeper processing compared to size judgements. During retrieval, source accuracy was also greater in the colour congruency encoding condition, whereas item memory (item hits and correct rejections) was consistent between the conditions. They claimed this may be an example of TAP (Morris et al., 1977), that is, that an overlap between the encoding and retrieval processes enhanced performance. In this case, the participants were asked to explicitly think about the item's colour both at encoding and at retrieval in the colour congruency task, whereas in the size judgement task it was only at retrieval that they were required to think about the colour. A Pearson's correlation showed no association between item accuracy and source accuracy in the size judgement encoding condition, which the authors considered to be consistent with the view that source memory requires additional processes that are not required for simple item recognition. However, item accuracy and source accuracy were found to be correlated in the colour congruency judgement encoding condition, which they argued was consistent with the view that binding the information at encoding made it more like a simple item recognition test. Source accuracy was also greater for Old-same than Old-different, regardless of encoding condition. Again, this could be supported by TAP (Morris et al., 1977) as there would be greater overlap between encoding and retrieval information for old-same items as they were presented in the same colour at study and test. Whereas, for old-different the colour information differed between study and test so there was less overlap.

Ecker et al. (2007) also used the same/different source three-button approach to examine whether manipulating the perceptual features of an image would impact recognition performance. They manipulated colour as either an intrinsic part of the image (image itself is coloured) or as an extrinsic part (a coloured border encases the image). In the test phase for each condition participants were required to respond whether the item was old-same colour to study phase, old-different colour to study phase, or a new item. They found that correct rejection of new items had the greatest accuracy, followed by accuracy for correctly identifying old-same colour, and old-different colour had the lowest accuracy. As seen in Kuo and Van Petten (2006) the differences in accuracy between old-same and old-different items could have been due to overlapping processes between encoding and retrieval in the same colour conditions (an example of TAP; Morris et al., 1977), whereas different colours caused a mismatch between the information at encoding compared to what was presented at test. However, there were no significant differences between the intrinsic and extrinsic conditions (i.e., item and source memory accuracy were the same regardless of whether the image itself was coloured or there was a coloured border) although reaction times were significantly slower in the extrinsic condition suggesting that the retrieval of intrinsic details is perhaps more automatic or based on a familiarity-based process.

Diana et al. (2011) also found evidence that suggested that familiarity-based processes can support source recognition when source information (red or green background colour) is integrated with the item (English nouns) at encoding. In the high-unitisation condition participants were instructed to imagine the subject of the noun in the colour shown in the background and to think about why it might be that colour, in order to encourage encoding of the item and source as a single unit of information. Whereas in the low-unitisation condition participants were asked to imagine why the word might be associated with a stop sign or a dollar bill (for the red and green backgrounds respectively). The behavioural results used receiver operating characteristic (ROC) analyses which were fit to a dual process signal detection (DPSD) model to estimate familiarity and recollection. They found that the familiarity estimate was higher in the high unitisation condition, whereas recollection did not differ significantly between conditions.

The neural basis of memory

Uncovering the neural processes involved in recognition memory helps us to understand the underlying processes involved in both encoding and retrieval. Electroencephalogram (EEG) measures electrical activity in the brain from electrodes on the scalp. The electrodes record the electrical activity generated by large groups of neurons acting in synchrony. Event Related Potentials (ERPs) are small changes in voltage at precise timeframes caused by a sensory, cognitive or motor event that allow us to observe brain activity at millisecond resolutions (Luck, 2005). A number of memory-specific ERP components during encoding and retrieval have been observed during a memory task (for a review see Voss & Paller, 2017).

The Dm effect (‘differential neural activity based on memory') refers to the observation that items that are subsequently remembered typically elicit a more positive waveform during encoding at 400-800ms after item onset, compared to those that are subsequently forgotten (Paller & Wagner, 2002). The hypothesis being that this more positive waveform reflects a superior encoding process. For example, Yovel and Paller (2004) presented participants with a stream of images of faces along with a spoken occupation for each face in a study phase. They observed a larger Dm effect for a longer time interval for recollection (in this example recollection was specified as being recall of the face, as well as the occupation that was paired with that face), compared to the Dm effect for familiarity (i.e., the face was recalled, but without the paired occupation). This suggested that the larger Dm reflected deeper/superior processing of the contextual information presented at encoding. However, Guo et al. (2006) found that the Dm effect did not differ according to whether the source (in this case whether the background shape of previously studied Chinese words was a circle or a square) was correctly or incorrectly identified. Therefore, it is possible that the Dm effect is dependent on the type of contextual information and/or its relationship with the item being studied. It could be argued that the nature of the study by Yovel and Paller (2004) encouraged greater semantic processing at encoding or particular strategies were used to remember the face and occupation combination. Participants were also asked to make a likelihood judgement at encoding which may have encouraged them to think of an association between the face and the occupation. This experiment is also closer to a real-world task compared to the Guo et al. (2006) study, i.e., remembering a person you've met and what they do for a living. It could also be argued that this task required greater cognitive processing as each face was paired with a unique occupation, therefore a larger number of contextual details were required to be memorised across the course of the experiment. Whereas in the Guo et al. (2006) study, participants had to only remember two possible contextual details, i.e., a square or a circle. The nature of the Guo et al. (2006) study also did not encourage participants to think of a relationship between the word and the background shape. Kuo and Van Petten (2006) also found significant differences between size judgement versus colour congruity judgement conditions in the 500-800ms time window (thus overlapping with the Dm effect interval) in parietotemporal regions during encoding, suggesting that some top down processes involved in binding item and source memory together (i.e. thinking about the relationship between the object and the colour) may also occur during this time interval.

Looking at the neural correlates of memory during the process of retrieval usually involves looking at ERP responses elicited by previously studied (old) items, compared to ERP responses to unstudied (new) items. Differences here are commonly referred to as old/new effects. The main old/new effect

ERPs that have been studied in relation to retrieval are the FN400 and the Late Parietal Component (LPC).

The FN400 is a negative component, occurring at around 300-500ms post stimulus over mid-frontal areas. This component has been associated with the process of familiarity or shallow processing; whereby items judged as new elicit a more negative (larger amplitude) ERP than items judged old/familiar (Curran, 2000). Rugg et al. (1998) also found that the ERP in the 300-500ms time interval over frontal areas during recognition was unaffected regardless of whether the words to be remembered were in the shallow or deep encoding condition. For source memory (or recollection of contextual information) the FN400 generally does not vary (e.g., Wilding et al., 1995, Wilding, 2000, Duarte et al., 2004, Woodruff et al., 2005). Guo et al. (2007) found that a similar FN400 effect was observed in the 300-500ms interval for Hits versus Correct Rejections of Chinese words, regardless of whether the background shape was also correctly identified or not. Kuo and Van Petten (2006) also found there was no difference between the encoding conditions (size judgement versus colour congruency judgement) for the old/new effects in frontal areas, although this effect was seen earlier than in other studies (around 200ms). However, Mollison and Curran (2012) found that the FN400 did reveal differences for source memory, but only when the context was spatial (i.e., whether the picture was presented on the left- or right-hand side of the screen), but not when the context was the colour of an outlined box, suggesting that the type of source information being retrieved may affect the FN400. Ecker et al. (2007) found that the FN400 old/new effect was eliminated when the item was presented in a different colour at test. This suggests that an old item in a new intrinsic colour is processed similarly to a new item. Whereas, in the extrinsic condition (coloured border) the FN400 old/new effect remained intact for items with a different border colour at test. They argued that intrinsic features are bound to the object at encoding, resulting in familiarity-based retrieval for items presented in the same colour at test. Based on this research it appeared that the FN400 is likely to reflect the difference in processing old versus new items, but whether (or how) it reflects memory for any contextual details or source information may be sensitive to the type of information presented and the cognitive processes required to encode it.

The LPC is a positive component observed over parietal electrodes in the 400-800ms interval and has been found to be more positive for old items than new items (Curran, 1999; Curran 2000). It is thought to reflect deeper, recollection-based processing (Curran, 2000; Dűzel et al., 1997; Rugg et al., 1998). The LPC has also been shown to have a larger amplitude for items accompanied by a correct versus incorrect source decision during the typical LPC time window of 400-800ms after stimulus onset (e.g., Woroch & Gonsalves, 2010, Wilding et al., 1995, Wilding, 2000, Duarte et al., 2004, Woodruff et al., 2005). Voss and Paller (2009) found that during a recognition test of geometric shapes using a remember/know confidence response the LPC was largest for 'Remember' Hits, followed by 'Know (high confidence)' Hits, followed by Correct Rejections, and lastly False Alarms which were smallest. They presented this as evidence that the LPC signals the success or strength of retrieval. The strength of retrieval indicated by the LPC was also found by Wilding (2000) who found that retrieval of words with two pieces of correct source information elicited a larger LPC effect than words retrieved with one piece of source information, and the LPC effect of words retrieved with one piece of source correct information was larger than correct rejections. However, in the study by Ecker et al. (2007) which manipulated intrinsic versus extrinsic source (coloured item versus coloured border) no LPC old/new effects were found. One explanation proposed for the intrinsic condition judgements was because the colour was intrinsically linked with the item it could retrieved by the more automatic process of familiarity rather than requiring the recollection-based processes indicated by the LPC. However, this does not explain the extrinsic condition. Therefore, they proposed that perhaps an additional process was used that was not apparent in the ERP results. It is possible that differentiating between same or different source in a recognition test requires different processes to when all source information is removed in the test phase. Overall, the research suggested that the LPC may be present when the information to be remembered requires a conscious retrieval of episodic or contextual details of the item.

Another component that has been studied in relation to memory retrieval is the Late Frontal Effect (LFE). The LFE is a later slow wave which is more sustained (around 600-1600ms) and most prominent over mid-frontal scalp sites. While this component does not appear to index retrieval success, it has been associated with effortful retrieval processes and post retrieval monitoring or evaluation. For example, Curran et al. (2001) found a greater positivity in the 1000-1500ms timeframe for old items and semantically similar lures than for new (unstudied) items, suggesting that this post retrieval evaluation is not necessary for rejecting new items but was required for the effort needed to discriminate between old items and lures.

These late frontal effects have also been associated with source memory. In Kuo and Van Petten's (2006) study, where the encoding condition required either a size judgement or a colour congruency judgement (with the intention that the colour congruency judgement would bind together the item and colour at encoding as one unit) they found late prefrontal old/new effects (greater positivity for old items ~700ms) were only seen in the size judgement encoding condition and not in the colour congruency judgement encoding condition. This suggests that attending to the colour at encoding eliminates the additional prefrontal neural activity required to retrieve source information. That is, the prefrontal activity was used to aid retrieval of weakly encoded relationships between attributes. Exploratory analysis by Ecker et al. (2007) in their study on intrinsic/extrinsic encoding conditions (coloured item versus border colour) also found some differential processing in the prefrontal cortex between items presented in the same colour between study and test compared to items presented in different colours between study and test (particularly so in the Extrinsic condition) in the 900ms-1200ms time window, which they suggested could reflect a control or evaluation based process. Overall, the research suggests that the LFE may be activated when an effortful or additional process is required to make a judgement for item or source memory.

The role of attention and types of processing on memory

In order for memory to be successful, information to be recalled needs to be effectively encoded, that is, sufficient attention and resources are given to processing that information. The way in which information is processed during encoding has been shown to modulate later recognition. In a classic study by Craik and Tulving (1975), participants were shown a list of words and for each word they had to answer one of three types of question, each designed to evoke a specific type of processing: structural, phonemic or semantic (to reflect shallow, intermediate and deep processing, respectively). When participants later had to pick out these previously studied words from a list, that also contained unstudied words, they found that participants were able to pick out more words that had been processed semantically, compared to words that had been processed structurally or phonemically. Semantic processing is thought to reflect a deeper level of processing, thus enhancing later retrieval.

Attention commonly refers to selectivity of processing, that is, selecting which information is relevant and which should be ignored. Our environment is often abundant in sensory information, however, what we are aware of in that environment can be selective and what we give attention to often depends on the task we are doing at the time. Attention can be controlled by top-down processes (e.g., wilful allocation of attention to a particular stimulus or spatial region) and/or bottom-up processes driven by external factors (e.g., properties of the stimulus itself such as shape, size, colour, or perhaps its sudden appearance). William James (1980) characterised these two types of attention as ‘active’ and ‘passive’. Several studies have shown that attention can modulate memory and the two processes are interdependent (see Chun & Turk-Browne, 2007, for a review). For example, Rock and Gutman (1981) found that when participants were instructed to selectively attend to one of two overlapping images, recognition of attended items was significantly greater than recognition of ignored items. This suggests that how information is attended to and processed during encoding affects how successfully it is later retrieved. Therefore, identifying conditions in which attention and processing can be optimised is of great interest in the field of memory research.

Temporal manipulations and the effect on memory

One area of interest is the impact of temporal structure on memory. Several studies have looked at the effect of temporal structure on other cognitive functions, including attention and perception, specifically, how the brain utilizes temporal information to make predictions about the future (Nobre & van Ede, 2018). Temporal expectation refers to the anticipation that an event will occur at a particular point in time. Large and Jones (1999) developed a hypothesis known as the Dynamic Attending Theory (DAT), which states that the dynamic structure of events can be used to selectively enhance attention to specific points in time. Within this they proposed that events, such as the presence of a rhythm, entrain peaks of attention focus creating a processing advantage for items occurring at attended compared to unattended attentional peaks. Entrainment refers to the observation that the internal neural oscillations of the brain (which are thought to reflect natural fluctuations in electric field potentials) have been shown to align with ongoing frequencies from external sources (Adrian & Matthews, 1934, Will & Berg, 2007, Spaak et al., 2014). It has been suggested that this entrainment is the mechanism behind the DAT by directing attention and information processing resources to specific points in time within the frequency wave, often defined as phase locking between neural oscillations and external stimuli, leading to selective attention, enhanced processing and superior subsequent memory (Lakatos et al., 2008, Calderone et al., 2014, Hickey et al., 2020). Another example of how rhythm can benefit processing of information was shown by Jones et al. (2002) who found that presentation of tones in synchrony with a rhythm improved the sensitivity of pitch discrimination compared with when tones were presented out of synchrony with the rhythm.

Recent evidence suggests that temporal expectation during encoding of new information can also improve later recognition memory for visual stimuli. Thavabalasingam et al. (2016) carried out a behavioural study, consisting of three experiments, looking at recognition memory for images of real-world scenes presented in a structured temporal timing versus unstructured temporal timing. Images were grouped into sets of four, with each set shown twice in succession during the study phase. The image onset timing was manipulated by varying the regularity of the inter-stimulus interval (ISI) between the individual images within each set. In the structured condition each image set followed the same regular fixed timing pattern for each repetition (e.g., onset of Image A = 500ms, onset of Image B = 1000ms, onset of Image C = 2000ms, onset of Image D = 100ms). Whereas, in the unstructured condition these timings were pseudo-randomised (such that the total duration of the intervals was the same in both conditions). They found that later memory for the images in a yes/no recognition task was greater in the structured condition compared to the unstructured condition in all three experiments. In Experiment 2 they included a two-stage response whereby after the participants responded to the yes/no question they were then presented with a 3-point confidence scale (1 – Very sure, 2 – Somewhat sure, 3 – Not sure). This allowed them to compute measures of familiarity and recollection using a dual-process signal detection model (Yonelinas, 1994). Based on this model they found that recollection was significantly lower in the unstructured than the structured condition. This suggests that the structured condition may enhance the ability to retrieve contextual details associated with the items studied, or that the unstructured timing is detrimental to the processing of these specific features.

Jones and Ward (2019) also examined the effects of temporal expectation on memory using an item recognition paradigm i.e., the ability to discriminate between previously studied (old) and unstudied (new) items. Specifically, they wanted to find out whether the presence of a rhythm during encoding influences later recognition. Their experiment consisted of six blocks and each block was made up of two tasks; a detection task (encoding phase) and a recognition task (retrieval phase). In half the encoding blocks images of everyday objects were presented in a rhythmic temporal structure and in the other half the images were presented in an arrhythmic temporal structure. As per the study by Thavabalasingam et al. (2016), temporal structure was manipulated via the timing of the ISI between images. In the rhythmic condition the ISI between images was held constant at 600ms creating an isochronous and predictable timing of image onset, whereas in the arrhythmic condition the timing of the ISI varied randomly between 70ms-1100ms, such that image onset was not predictable. While participants were aware that their memory for the items would be tested, they were not informed of the temporal manipulation. To ensure participants attended to the images throughout the detection task they were instructed to respond via a keyboard press whenever they saw an image of animal. Each detection task was followed by a recognition task in which participants were presented with the same images of objects from the prior detection task, along with an equal number of new (unstudied) images. For each image, participants had to judge whether it had been previously presented in the prior detection task or was new. Participants responded via a 6-point confidence scale whether the object was shown in the previous detection task where 6 = sure yes, 5 = think yes, 4 = guess yes, 3 = guess no, 2 = think no, 1 = sure no. These were collapsed into 'yes' or 'no' responses for analysis and then sorted into one of four categories, Hits, Misses, False Alarms, Correct Rejections. Jones and Ward (2019) found that rhythmic presentation of stimuli resulted in a greater recognition of items, compared to recognition of items encoded under arrhythmic presentation. In this study they also recorded EEG during both the encoding and retrieval tasks to see if there were any differences in neural activity between the two temporal conditions. At encoding they found that there was a greater Dm effect for rhythmic items compared to arrhythmic items, suggesting processing differences between the two conditions. During recognition they found that the FN400 old/new effect was present in both the rhythmic and arrhythmic conditions. However, the LPC old/new effect was only observed in the rhythmic and not the arrhythmic condition, which also indicated that temporal presentation may result in processing differences. One possibility is that rhythmic presentation creates optimal conditions or peaks of attention focus (as per the Dynamic Attending Theory; Large & Jones, 1999) for processing perceptual information or for deeper encoding creating a stronger memory trace for later retrieval, which could explain the differences seen for the memory specific components (the Dm effect and LPC) between the two conditions.

Based on the dual process model of recognition, these differences could also reflect that rhythmic encoding is associated with recollection-based processing, rather than familiarity-based processing. Evidence for this is that the LPC, that was present only for rhythmically encoded items, has been associated with recollection-based processing (Curran, 2000). Alternatively, arrhythmic presentation could be disruptive to optimal processing conditions by creating interference during rehearsal after image offset (Proctor, 1983) potentially resulting in shallower processing. They also looked at whether the neural data provided any evidence of entrainment in the presence of stimuli presented in a rhythmic structure, specifically looking at early perceptual components P1 and N1 during the encoding phase to see if there were any differences between the two temporal conditions. This could indicate a perceptual processing advantage which could perhaps support the DAT. No effect was found for P1 between the two temporal conditions. There was also no effect of temporal structure on the N1 for objects only, however, there was a significant difference between rhythmic and arrhythmic checkboards. In addition, they looked at phase locking factor (PLF), also known as inter-trial coherence (ITC), to see if the peaks of internal oscillations aligned with the external rhythm of the presented stimuli. They found that there was a higher PLF in the rhythmic condition compared to the arrhythmic condition, which could be taken as evidence for entrainment. However, it is difficult to ascertain whether this finding truly reflected entrainment or was simply a result of evoked responses due to the images flashing on the screen at that time.

More recently, Jones et al. (2022) examined how temporal expectation interacts with spatial attention and its impact on recognition memory and the associated neural components. This experiment consisted of eight blocks, each with a detection task (encoding phase) and a recognition test (retrieval phase). At encoding participants were presented with an object and checkerboard pair, or a pair of checkerboards, and were cued whether to covertly attend to either the left- or right-hand stimuli and detect targets (pictures of animals) on the attended side by pressing the spacebar. In half the encoding blocks the presentation of stimuli was rhythmic, and in the other half the presentation was arrhythmic. Presentation timings were manipulated via the ISI and followed the same timing structure as the Jones and Ward (2019) study detailed above. In addition, in half the blocks participants were cued to attend to items on the left and in the other half they were cued to attend to items on the right. EEG was also measured throughout the experiment. Behavioural analysis revealed an interaction between temporal expectation and spatial attention, whereby recognition accuracy was greater in the rhythmic condition for spatially attended items compared to spatially attended items in the arrhythmic condition. This greater recognition in rhythmic encoding conditions compared to arrhythmic encoding conditions is consistent with the previous research on temporal expectations (Thavabalasingham et al., 2016; Jones & Ward, 2019), whereby temporally predictive presentation of items significantly bolstered memory. However, there was no effect of temporal condition on recognition accuracy for unattended items, suggesting that rhythmic presentation can only provide optimal encoding conditions when the stimuli are attended to. The ERP results showed that the FN400 and LPC old/new effects were present for attended items in both the rhythmic and arrhythmic conditions. Whereas, for unattended items there was an FN400 old/new effect for both rhythmic and arrhythmic conditions but no LPC old/new effect for either temporal condition. When the attention conditions were directly compared, a larger LPC amplitude was found for attended items compared to unattended items, but no significant difference between attended and unattended items in the FN400 time interval. This suggests deeper / recollection-based processes (associated with the LPC) were utilised for attended items but not for unattended items, whereas shallow / familiarity-based processes (associated with the FN400) were present for both attended and unattended items.

Aims of the current study

While Thavabalasingham et al. (2016) proposed that structured presentation may affect recollection (according to a dual-process model) through their use of a confidence scale, to our knowledge, the effect of temporal structure on source memory (i.e., recalling a specific contextual detail of a memory) has never been investigated. Specifically, we were interested in finding out the impact of rhythm during encoding on source memory. Therefore, the present study aimed to shed light on whether rhythmic presentation boosts this more detailed form of memory.

We investigated the following research questions with the use of behavioural and EEG measures. Firstly, we wanted to find out whether the effect of rhythm on item recognition and memory specific ERP components (seen in Jones & Ward, 2019) could be replicated. In addition to this we also wanted to find out if the effect of temporal manipulation extended to source memory i.e., is source memory affected by rhythmic presentation of stimuli? Moreover, we wanted to investigate whether there are differences in the neural processes that support source memory in the rhythmic and arrhythmic conditions. In the current study we aimed to answer these questions by extending the experimental paradigm used by Jones and Ward (2019). That is, participants were presented with a stream of images of everyday objects during an encoding phase prior to a recognition task. Within each encoding block the presentation timing was either rhythmic or arrhythmic. To enable measurement of source memory, each item in the encoding phase was presented with either a cyan (blue) or magenta (pink) border. Thus, at the recognition task participants had to make a judgement whether the item was presented in the previous encoding task with a blue or pink border, or was new.

We predicted that the rhythmic encoding condition would lead to greater recognition of items at the subsequent recognition test, compared to the arrhythmic condition. Moreover, we expected that the FN400 old/new effect would be present in both the rhythmic and arrhythmic conditions, whereas the LPC old/new effect would be present in the rhythmic condition only. These predictions were based on an assumption that the current study would show a replication of the findings from the Jones and Ward (2019) study. We also made a number of predictions about source memory. If rhythmic encoding is associated with deeper / recollection-based processing, then we predicted that source accuracy would also be greater in the rhythmic condition compared to the arrhythmic condition. We also expected the FN400 old/new effect would be present regardless of source judgement (based on the findings from Guo et al., 2006) and present in both temporal conditions (as per Jones & Ward, 2019). We expected the LPC old/new effect to be larger for correct source judgements compared to incorrect source judgements (based on Woroch & Gonsalves, 2011) and if rhythmic presentation promotes deeper / recollection-based process we expected this effect to be greater in the rhythmic condition. If the LFE old/new effect reflects effortful retrieval then we may expect this effect to have been larger in the arrhythmic condition.

Pre-registration (Open Science)

Prior to commencing data collection this study was pre-registered on the Open Science Framework (OSF). The OSF in an online platform which aims to promote the integrity of scientific research by encouraging research that is transparent and reproducible. Research journals often only publish studies which have been successful and have significant results, whereas the OSF believe that research is still valuable even when it does not go as expected, and sharing null findings are still beneficial to the scientific community as it allows you to check if similar research is being carried out elsewhere and for findings to be shared across institutions. Pre-registration involves uploading a research plan onto the OSF platform prior to data collection, including the research questions, variables, hypotheses, methods and analysis, as well as the rationale behind them. Once finalised it is time stamped with a permanent digital object identifier (DOI). The benefit of pre-registration is that by providing transparency of all the steps of the research upfront it prevents practises such as p-hacking, cherry picking or hypothesising after the data has been analysed. It also makes the study more accessible to others in the scientific community and allows for future replication and collaboration. Pre-registration is also often required by funding agencies. The pre-registration for the current study can be found on the OSF website here: https://osf.io/zy2pd

The specific, detailed hypothesis produced for the pre-registration were as follows:

Hypothesis 1: For item memory we predicted significantly greater item recognition in the rhythmic than the arrhythmic condition. This is based on Jones and Ward (2019), who found greater recognition in the rhythmic than the arrhythmic condition.

Hypothesis 2: For source memory we predicted a significantly greater source memory (proportion correct colour judgements) in the rhythmic than the arrhythmic condition. Although this was the first study to examine the effect of rhythmic encoding on source memory, there is evidence that rhythmic encoding is associated with greater/deeper processing of items (Thavabalasingham et al., 2016; Jones & Ward, 2019) that may support recollective retrieval required for source memory.

Hypothesis 3a: At encoding we predicted a larger positivity of rhythmic over arrhythmic stimuli as seen in Jones and Ward (2019).

Hypothesis 3b: We also we predicted a more positive waveform at 400-800ms for items remembered than items forgotten (Dm effect) as seen in Paller and Wagner (2002). However, this could only be analysed if there were enough misses in each condition and this was not the case in Jones and Ward (2019) so we had no prior knowledge whether temporal condition would interact with item type. We proposed that a minimum of 20 Hits and 20 Misses per condition is required and a minimum of 23 participants (to be comparable with the final sample in Jones & Ward, 2019).

Hypothesis 3c: We also did not expect the Dm effect to interact with source accuracy. That is, items associated with both correct and incorrect source judgements for Hits would both be more positive than items forgotten (misses), but no effect between source correct versus incorrect as per Guo et al. (2006). This analysis was also on the provision of a sufficient number of source correct and source incorrect trials. Again, we proposed that a minimum of 20 source correct and 20 source incorrect per condition was required and a minimum of 23 participants.

Hypothesis 4: At retrieval we predicted a FN400 old/new effect for item memory (i.e. Hits vs Correct Rejections) in both the rhythmic and arrhythmic conditions, with a more negative/larger amplitude waveform for new items (Correct Rejections) than old items correctly identified as old (Hits) and we expected no interaction with temporal structure.

Hypothesis 5: For source memory, based on Guo et al. (2006) we expected an FN400 effect between old and new items regardless of accuracy of source judgement and no FN400 effect of source accuracy with no interaction with temporal structure.

Hypothesis 6: We also expected a significantly greater LPC old/new effect in the rhythmic than the arrhythmic condition based on the results seen in Jones and Ward (2019).

Hypothesis 7: We expected a larger LPC effect for correct source judgements relative to incorrect source judgements (based on Woroch & Gonsalves, 2011), and we expected this to interact with temporal structure, with a greater effect in the rhythmic than the arrhythmic condition in line with Jones and Ward (2019).

Hypothesis 8: No item recognition studies had yet looked at the effects of temporal structure on the LFE. However, as this component has been show to reflect effortful retrieval we may have expected a larger old/new effect in the arrhythmic than the rhythmic condition.

Discrepancies within the OSF pre-registration

There were a few discrepancies in the OSF pre-registration compared to what was done. Firstly, in the OSF in the analysis for Hypothesis 3a we said we would also analyse animals (as well as objects and checkerboards) in the item type for the Dm effect. However, we also specified we would use a 2x2x2 ANOVA, whereas to include animals this would be a 2x2x3 ANOVA. Therefore, in the analysis we decided just to use a 2x2x2 ANOVA and only include objects and checkerboards in the item type. The analysis for Hypothesis 3b/3c we originally stated that we would do a 2x2x2x2 ANOVA that combined item and source memory into one analysis. However, as we did not have enough misses on item memory a 2x2x2 ANOVA with factors of Temporal Condition (rhythmic, arrhythmic), Subsequent Source Response (source correct, source incorrect) and Electrode (PO7, PO8) was used instead on a subset of 23 participants who had achieved at least 20 trials source correct and 20 trials source incorrect in both conditions. Another discrepancy was we stated in Hypothesis 8 in the OSF that the time interval for LFE analysis would be 800-1200ms. However, we had already stated that the data would be epoched into 1100ms, with 100ms before and 1000ms after stimulus onset and that the LFE would be analysed in the 800-1000ms interval. Therefore, the actual interval used for LFE analysis was 800-1000ms.

Method

Participants

Thirty-four participants took part in the experiment. They consisted of students from Middlesex University London and residents from the local area. Participants were required to be aged 18-35 years to take part and were recruited via opportunity sampling, which included word of mouth and posters put up around the university campus. Participants were also required to be free of photosensitive epilepsy due to the task consisting of flashing images. Three participants were excluded prior to analysis, one for failing to complete the full experiment due to a technical error, one due to later revealing they were outside the recruitment criteria for age, and one due to not meeting the detection threshold in the detection task, as specified in the OSF (i.e., failing to detect at least 80% of targets overall during the encoding phases). This resulted in a final sample of thirty-one usable participants' data for analysis. The mean age of the participants was 27.39 years (SD = 4.92), and the sample comprised 23 females and eight males. Three participants were left-handed and 28 were right-handed. All were fluent in English language and had normal or corrected to normal vision and had no form of colour blindness. This was to ensure participants would be able read and understand the instructions, to see the images presented on the screen clearly and able to distinguish between the two stimulus border colours.

The sample size and criteria were based on previous research by Jones and Ward (2019) who had 23 usable participants in their analysis, with an effect size of d=0.30. This was raised to 32 participants in the present OSF pre-registration to allow for full counterbalancing of the 16 conditions. While we endeavoured to replace all three participants that had to be excluded, due to the timing of the MSc submission we were only able to replace two out of the three needed within the timeframe. Therefore, the sample size was one less than originally planned and resulted in a final sample size of 31 participants for analysis.

The research study was granted ethical approval by the Middlesex University Research Ethics Committee (approval code: 8702). All participants provided written informed consent prior to taking part, whereby the participant was informed of the purpose of the research, what would happen in the study and were given the opportunity to ask questions. It should be noted that the participants were informed that the purpose of the study was ‘to investigate recognition memory performance for visually presented objects and the associated brain activity’ but they were not informed about the temporal manipulation. They were also informed that their participation was voluntary and that they could withdraw at any time without giving a reason and without penalty. Participants were also informed that all procedures adhered to the General Data Protection Regulation (GDPR) and it was explained to them how the data would be used, who it would be shared with, how it would be stored, and how long it would be kept for. They were informed that their individual data would remain anonymous, such that no one would be able to identify them from the data. A cut-off date and contact details were also given to the participant should they wish to withdraw their data prior to analysis. At the end of the experiment participants were thanked for their participation and fully debriefed. In the debriefing they were informed of the temporal manipulation within the experiment. They were also encouraged to get in touch should they have any further queries and the relevant contact details were provided via a debriefing sheet. In exchange for their participation, all participants received a £20 Amazon gift voucher. The value of this incentive was based on a total participation time of 2-2.5 hours including set up, completing the task, and hair washing and debriefing time afterwards.

Design

The design of the experiment was closely modelled on Jones and Ward (2019) to allow for comparability. The experiment consisted of a within-participants (repeated measures) design. The independent variable was the presentation timing of images during encoding, that is, temporal condition with two levels (the images were either presented rhythmically or arrhythmically). The dependent variables measured were the effect of this temporal manipulation on behavioural item and source recognition accuracy, and neural activity (i.e., differences in ERPs between the two conditions). Specifically, the Dm effect during encoding, and three ERPs associated with memory during retrieval, namely the FN400, Late Positive Component (LPC) and the Late Frontal Effect (LFE). The electrode and time interval choice for the Dm effect, FN400 and LPC were chosen on the basis of replicating the Jones and Ward (2019) study. Namely, electrodes PO7 and PO8 in the time interval 400-800ms after stimulus onset for the Dm effect; electrode Fz in the time interval 300-500ms after stimulus onset for the FN400; and electrode P3 in the time interval 400-800ms after stimulus onset for the LPC. These were also the same electrodes and time intervals used in a study by Bergström et al. (2016) who looked at the effect of distractor stimuli on recognition memory and how this affected the neural correlates of memory. As the LFE was not studied in Jones and Ward (2019), the electrode choice (F2) was based on Curran et al. (2001), who found that right frontal ERPs were more positive for targets and lures compared to new items, which they suggested reflected post-retrieval evaluation or effortful processes required to distinguish between semantically similar targets and lures. In this study we hypothesised that an effortful process could also be required to recall the source information as the attentional demand is higher. The time interval for the LFE starting at 800ms was chosen on the basis of a study by Wolk et al. (2009) who found that recognition Hits had a more positive voltage than Correct Rejections in older participants beginning from 800ms until the end of the recording epoch. This effect was found to be more prominent among participants who had performed poorly in the task compared to those who had performed well, which was interpreted to reflect a retrieval function in prefrontal regions to compensate for a lack of success in earlier retrieval processes, perhaps due to a weak memory trace. The cut off for the time interval for the LFE in this study was limited to 1000ms due to the need to replicate the design of Jones and Ward (2019) in which each image in the recognition phase was shown for 1000ms before the response options were shown.

A blocked design was used, with each participant exposed to a total of six blocks. Each block consisted of two phases; an encoding phase and a recognition phase. For participants, we named these two phases the ‘Detection Task’ and the ‘Memory Task’, respectively. Of the six blocks, three had rhythmic presentation of stimuli during the encoding phase, and three had arrhythmic presentation of stimuli. Thus, half of the blocks were in the rhythmic condition, and half in the arrhythmic condition. The presentation of rhythmic and arrhythmic blocks was alternated between participants, such that the same temporal condition was not shown consecutively. Half of the participants were shown the rhythmic block first and half were shown the arrhythmic block first (i.e., half of the participants witnessed the blocks in the order Rhy-Arr-Rhy-Arr-Rhy-Arr, and half witnessed the blocks in the order Arr-Rhy-Arr-Rhy-Arr-Rhy).

Stimuli

The stimuli were 400 x 400 pixel images of everyday objects (e.g., an apple, a chair) taken from the Bank of Standardized Images (BOSS) (Brodeur et al., 2014) (see Figure 1 for examples). This was the same bank of images used in Jones and Ward (2019). All images were greyscale, presented on a white background.

Forty unique images of objects were shown in each encoding phase. In each recognition phase the 40 images from the encoding phase immediately prior were shown, along an additional 40 new images not shown elsewhere in the study. Therefore, there was a 50:50 ratio of old to new images in the recognition phase and participants were informed that there would be an equal number of old and new items. This was to ensure in the event of a guess responses, participants knew there was an equal probability of an object being old or new. Across the six blocks of the experiment a total of 480 unique images were presented to participants (240 old and 240 new).

Within each encoding phase 120 checkerboards (also 400 x 400 pixels) were interspersed throughout so that there was a 3:1 ratio of checkerboards to objects (see Figure 1 for example checkerboard). The purpose of the checkerboards was to extend the length of the encoding phase and to allow a perception of rhythm (or arrhythm) to build. At least one checkerboard was presented after each object such that two objects were never presented consecutively. The area of the checkerboard was the same size as the area covered by the object.

In addition, between two and six images of animals were added to each encoding block (see Figure 1 for example). These counted for 10% of trials across the overall experiment. Three additional checkerboards were added for each animal to maintain the 3:1 ratio of images to checkerboards. The purpose of including images of animals was to serve as targets that the participants had to detect to ensure that they were paying attention to the task. No images of animals were shown in the recognition phase.

In order to measure the effect of temporal presentation of images on source memory a 15-pixel border was added to each image in the encoding phase, taking the total image size including the border to 430 x 430 pixels. Borders were added using Faststone Photo Resizer 4.3 (www.faststone.org). The border colours used were cyan (RGB=0,255,255) and magenta (RGB=255,0,255) (see Figure 1 for examples). These were referred to in the experiment as ‘blue’ and ‘pink’ for simplicity for the participants. The colours were chosen as they were felt to be equal in terms of brightness and luminance, while also able to be discriminated between even if the participants had colour-blindness, unlike red and green used in previous source memory studies (although normal vision was specified as a requirement for participation as a precaution). The rationale behind choosing a border colour rather than a background colour or colouring the image itself is firstly to keep the images themselves consistent with those used by Jones and Ward (2019), and secondly to match the objects at encoding and test. That is, the objects themselves were presented in greyscale during both encoding and test so the perceptual features of the objects remained consistent. Ecker et al. (2007) found no difference in item or source memory accuracy regardless of whether the objects themselves were coloured or presented within a coloured border. Within each encoding block, half of the images of objects had a cyan border and half had a magenta border. Again, participants were informed of this 50:50 ratio so that in the event they weren't sure of the border colour when it came to make this decision at test and had to make a guess they knew that there was an equal probability of it being previously blue or pink. All images of objects in the recognition phase were shown without any borders.

Images of animals in the encoding phases also had either a cyan or magenta border. Each encoding phase had at least one animal with a cyan border and one animal with a magenta border. The border colour of any additional animals shown were randomly assigned to cyan and magenta but such that no more than a total of three animals with a cyan border and three animals with a magenta border were shown. The rationale for presenting the animals with a coloured border was so that participants would need to attend to the image itself to decide whether it was an animal rather than base this decision on the absence of a border.

Checkerboards did not have any coloured borders. The rationale for not giving checkerboards coloured borders was to limit source features to the objects that participants were tested on in the recognition phase, and prevent making the experiment too difficult, such that any effect from temporal condition on source memory could be lost.

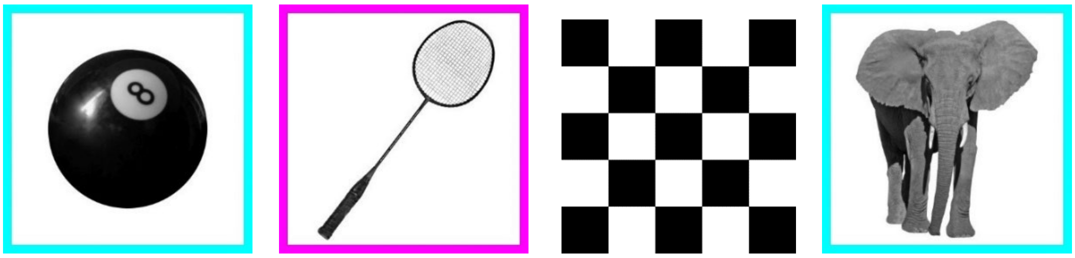


Figure 1. *Example stimuli from the encoding phase.*

Note. (l-r) Image of an object with a cyan border, image of an object with a magenta border, image of a checkerboard, image of an animal with a cyan border. Each stimulus was presented one at a time.

In order to program the experiment, images of objects from the Bank of Standardized Images (BOSS) (Brodeur et al., 2014) were split into twelve sets of 40. The order in which objects were presented in the encoding phase was randomly assigned, such that there was no duplication between participants. Likewise, in the recognition phase the order of old and new images was randomised with no duplication.

Image sets were also counterbalanced between whether the images were presented as old (studied) or new (unstudied). That is, for half of the participants half of the image sets (i.e., even sets) were presented as old and the other half (i.e., odd sets) were presented as new items, and these sets were switched for the other half of the participants (i.e., odd = old items and even = new items).

To counterbalance object border colours in the encoding phase, each set of 40 was split into two versions (A and B). In Set A images 1-20 had a blue border, and images 21-40 had a pink border. In Set B images 1-20 had a pink border, and images 21-40 had a blue border. This was to ensure that across the study all images had a blue border version and a pink border version. Participants would only see one version of each object throughout the test by counterbalancing between participants whether they see Set A or Set B in each block.

The image sets were also counterbalanced between blocks such that each stimulus set appeared an equal number of times in each block across the experiment. The purpose of counterbalancing the images sets was to ensure that any potentially distinctive images did not confound one condition over the other.

The counterbalancing and rotation detailed above resulted in sixteen unique variations of the experiment for participants to be assigned to. The block order was changed after each participant in a numerically chronological order and the image condition was changed every fourth participant to ensure equal variations of block order and image condition across the experiment.

Procedure

The task was programmed in E-Prime 3 and presented on a PC with a screen resolution of 1920 x 1080 pixels. All responses were given via a keyboard keypress. Participants completed the experiment individually in a sound attenuated booth. The duration of the experiment was around one hour (excluding EEG set up and debriefing).

Participants were told that the experiment was made up of six blocks, and within each block there were two tasks; a Detection Task and a Memory Task, in between which there would be a one minute mental arithmetic filler task. The inclusion of the mental arithmetic task was to minimise any recency effects from the encoding phase. Participants were given the instructions verbally prior to starting the experiment, as well as on screen during the experiment itself, where relevant.

For the Detection Task (see Figure 2) participants were told that they would be shown 40 unique images of objects on the screen, one at a time, in quick succession. Half of these images would have a blue border and the other half would have a pink border. They were told that in between these images of objects there would be images of black and white checkerboards, which would make up the majority of the images shown. In addition, they were informed that on average 10% of images would be animals. They were instructed that their task was to press the spacebar on the keyboard as quickly as possible whenever they saw an image of an animal. All images (objects and animals) and checkerboards were presented for the same fixed duration, 600ms, in both the rhythmic and arrhythmic conditions. In between each item (object/animal/checkerboard) a fixation point was presented in the centre of the screen during the interstimulus interval (ISI). The length of time this fixation point was presented varied between the two temporal conditions. In the rhythmic condition, the ISI was presented for 600ms consistent with the timing of each item in order to create an isochronous rhythm. In the arrhythmic condition the ISI was presented for a randomly drawn duration ranging between 70-1130ms. The timings in the two conditions replicated the timings used in Jones and Ward (2019). The average duration of the ISI was equal across the rhythmic and arrhythmic conditions. The ISI was used to manipulate the presentation timing so that the amount of time participants were shown the images for was consistent across the two conditions, so that any differences in dependent variables could be attributed to the temporal structure, rather than differences in the duration of exposure to the images. Participants were not informed of the temporal manipulation until after they had completed the full experiment.

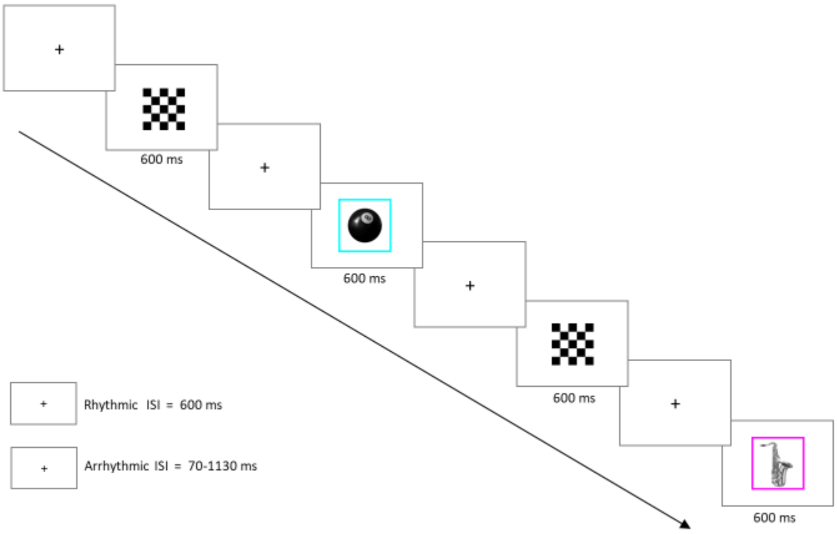


Figure 2. *Events in the encoding phase (Detection Task).*

For the Memory Task (see Figure 3), participants were informed they would see the 40 images of objects from the prior encoding phase, as well as an equal number of new images of objects. They were shown one image at a time and instructed to respond to the question “Was this image shown during the viewing task” via a three-button keyboard press using the numbers 1=Yes (blue border), 2=Yes (pink border) or 3=No whether they believed the object was presented before with a blue border or a pink border, or whether it was new. We opted for a three-button response (as opposed to a sequential or exclusion response, as detailed in the introduction), to allow measurement of the neural components to be measured simultaneously for both item and source memory and also to maintain the 50:50 probability between old and new items as per Jones and Ward (2019). Participants were instructed that if they recognised the item but were unsure of the source then to guess one of the source options, so that item memory accuracy would not be impacted by unsure source responses. The layout of the response screen also grouped the two source responses on one half of the screen and the new responses on the other half to try and keep it closer to a binary response. We also opted to present items without any source information at test (i.e., no border), rather than present items with either the same or different colour border at test. Given that neural differences were found between the old-same source and old-difference source trials in previous studies using same/different response approach (Kuo & Van Petten, 2006; Ecker et al., 2007) but not between the old-source A and old-source B trials used in the study by Guo et al. (2006) we opted for the same approach as Guo et al. Therefore, the neural activity of source memory could be measured by collapsing correct source responses, regardless of colour, without interference from any potential neural differences by re-presenting the same item-source combination at test. The object was displayed on the screen for 1000ms after which the instructions “Was this object shown in the last detection task?” appeared for the participant to respond. The 1000ms presentation of the image prior to the question onset was based on the timing of the LFE ERP in previous literature. No time limit was imposed for participants to give their response. Once the participant had given their response a fixation point was presented on the screen for a duration ranging between 70-1130ms prior to the onset of the next image.

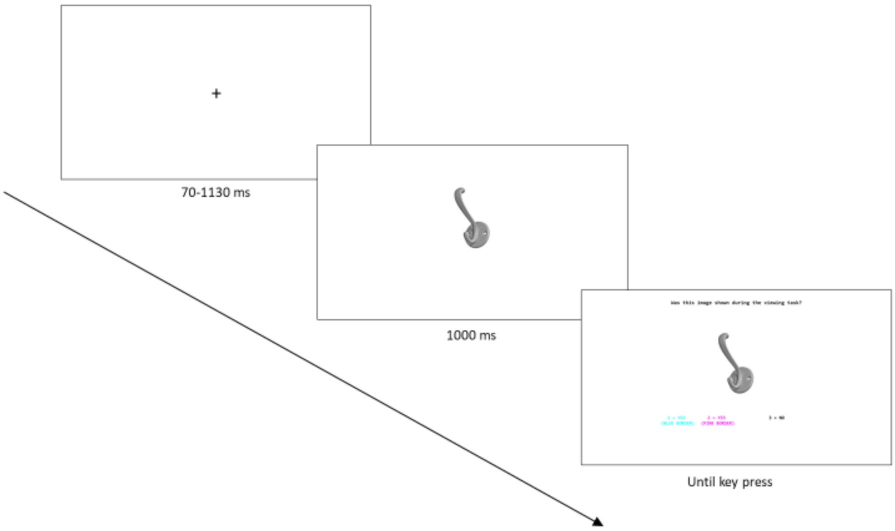


Figure 3. *Events in the recognition phase (Memory Task).*

Prior to the main experiment, participants were given two short practice blocks (one rhythmic, one arrhythmic - the order of which was rotated between participants). Each block consisted of three detection trials and six recognition trials (half old, half new). The inclusion of these practice blocks was to ensure that the participant understood what they needed to do before the recording commenced.

After the participant completed the experiment they were given a standardised awareness questionnaire (see Figure 4) to examine whether they noticed the temporal manipulation. If they reported noticing any differences between blocks, they were asked to describe them and whether they became aware of them during or after the experiment. Open ended questions were used in the awareness questionnaire so that the participant could give a free form answer and weren’t prompted by a list of pre-populated answer choices. If a participant mentioned a difference in timing, even if they couldn’t describe exactly what it was or how it was manipulated, then they were labelled as ‘aware’.

Q1	Did you notice any differences between blocks in the computer task? If so, please explain here:
Q2	Each block consisted of a Detection Task and a Memory Task. In the Detection Task, you pressed the Space bar whenever you saw an animal. Did you notice any differences in the Detection Task between blocks?
If you answered 'No' to Q2 above, then you do not need to complete the rest of the form. ***If you answered 'Yes' to Q2 above, please continue:***	
Q3	If you think that there was a difference in the Detection Task between blocks, what do you think this was?
Q4	If you think that there was a difference in the Detection Task between blocks, did you notice this during the task, or did you become aware of this afterwards/in hindsight?

Figure 4. *Awareness questionnaire*

EEG recording and pre-analysis processing

During both the encoding and recognition phases EEG was recorded from 64 active electrodes using Brain Products ActiChamp EEG system.

During recording, each event of interest had a unique marker code that time-stamped the onset of the event onto the EEG data. The specific events of interest in the encoding phase were image onset (split by type of image – object, animal or checkerboard, border colour and temporal condition) and the response for that image at the subsequent retrieval phase (Hit, Miss, Correct Rejection or False Alarm for item memory, and Source Correct or Source Incorrect for source memory). In the recognition phase these were image onset (split into old or new image, previously blue or previously pink borders, and temporal condition during encoding) and response (Hit, Miss, Correct Rejection or False Alarm for item memory, and Source Correct or Source Incorrect for source memory).

Pre-processing of the EEG data was conducted in Brain Vision Analyzer 2.2 (Brain Products GmbH). Firstly, a zero-phase shift Butterworth filter with a low cut-off of 0.1Hz and high cut-off of 40Hz and with a 50Hz zero-phase notch filter (to remove any noise generated by the mains) was applied to each participant's continuous data. Secondly, any bad channels were interpolated manually on a participant-by-participant basis. Seven participants had between one and five channels interpolated based on the data from other surrounding electrodes and their location on the scalp (across all participants a total of 23 channels were interpolated). No channels that were included in the analysis (i.e., Fz, F2, P3, P07 or P08) were interpolated. Thirdly, data was re-referenced from the old reference FCz used at recording to the average of all 64 electrodes instead. In the final step of the pre-processing components associated with eye blinks were identified and then removed, using independent component analysis in a semi-automatic mode.

Encoding data was epoched into 900 ms segments (100 ms pre- and 800 ms post- stimulus onset) and retrieval data was epoched into 1100 ms segments (100 ms pre- and 1000ms post- stimulus onset). Including the 100 ms pre- stimulus onset was so that the relative change in electrical activity after stimulus presentation could be measured. Therefore, a 100-ms pre- stimulus baseline correction was performed on each segment by subtracting the mean voltage in that interval from every voltage point (1/ms) in the ERP. The final step in cleaning the data was artifact rejection. This was performed on all channels, excluding segments with amplitudes of ±100 µV.

Once the data had been pre-processed, segmented and cleaned, repeated trials within the same condition were then averaged together across the multiple trials in the experiment. This was to obtain reliable ERP data by averaging out any background EEG signals that do not occur at a consistent time point across multiple trials. Each time interval was analysed using a repeated measures ANOVA and the effect size measured by partial eta squared (η_p^2).

Results

An alpha level of .05 was used for all statistical tests as the criterion for rejecting the null hypothesis.

Behavioural Results

Detection Task

The mean proportion of targets (animals) correctly detected, the mean proportion of erroneous key presses to non-targets (non-animal objects or checkerboards), and the response times (RT) in milliseconds (ms) for correctly detected targets were calculated for both the rhythmic and arrhythmic conditions (Table 1). Two-tailed paired samples *t*-tests uncovered no significant differences between the rhythmic and arrhythmic conditions in terms of correct detection of targets, *t*(30) = .41, *p* = .684, *d* = .074, erroneous key presses to non-targets, *t*(30) = .86, *p* = .397, *d* = .154, or RTs, ; *t*(30) = .27, *p* = .788, *d* = .049.

Table 1.

Performance in the Detection Task, averaged separately across the Rhythmic and Arrhythmic blocks.

	Rhythmic blocks Mean (SD)	Arrhythmic blocks Mean (SD)
Correct detection of targets (%)	96.70 (4.88)	97.04 (4.61)
Erroneous key presses to non targets (%)	0.14 (0.19)	0.19 (0.25)
RT of correctly detected targets (ms)	576 (88)	573 (92)

Memory Task: Item recognition

In order to calculate item recognition, ‘previously pink’ and ‘previously blue’ responses were collapsed into a single ‘old’ judgement. The output from the memory task resulted in proportions and corresponding RTs for the following four measurements for item recognition: ‘Hits’ (old items correctly identified as old), ‘Misses’ (old items incorrectly identified as new), ‘Correct Rejections’ (new items correctly identified as new) and ‘False Alarms’ (new items incorrectly identified as old). The proportion of each and the corresponding RTs can be found in Table 2.

Item recognition was measured by the statistic d-prime (d’) which was based on the signal detection model by Snodgrass and Corwin (1988) whereby a numerical estimate of sensitivity/recognition accuracy was applied (Z-transformed probability of Hits)–(Z-transformed probability of False Alarms). A correction was also applied to any Hit or False Alarm scores with a value of 0 or 1: Corrected Hit rate: (n Hits + 0.5) / (n old items + 1), Corrected False Alarm rate: (n False Alarms + 0.5) / (n new items +1). See Figure 5 for overall d’ scores in the rhythmic and arrhythmic conditions.

A one-tailed paired *t*-test showed no significant difference in item recognition (d’) between the rhythmic and arrhythmic blocks: *t*(30) = 1.47, *p* = .075, *d* = .265.

Table 2.

Proportion of hits, misses, correct rejections, and false alarms and their corresponding Response Time (RT) in milliseconds (ms), averaged separately across the Rhythmic and Arrhythmic blocks.

	Rhythmic blocks	Arrhythmic blocks
	Mean (SD)	Mean (SD)
Proportion of Hits	0.79 (0.15)	0.79 (0.13)
Proportion of Misses	0.21 (0.15)	0.21 (0.13)
Proportion of Correct Rejections	0.88 (0.12)	0.89 (0.14)
Proportion of False Alarms	0.12 (0.12)	0.11 (0.14)
RT Hits	968 (561)	1033 (600)
RT Misses	892 (530)	809 (451)
RT Correct Rejections	596 (291)	640 (284)
RT False Alarms	1224 (715)	1639 (1358)

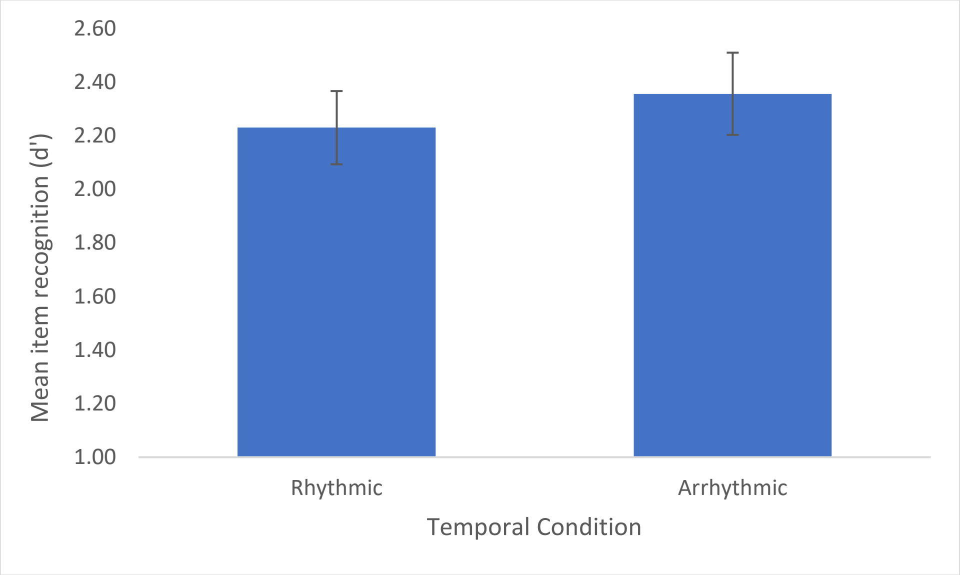


Figure 5. *Correct recognition (d') in the Memory Task for item recognition, averaged separately across the Rhythmic and Arrhythmic blocks. (standard error bars).*

Memory Task: Source recognition

In order to calculate a source memory score (i.e., the proportion of correct colour judgements) for each participant, correct responses for 'previously pink / previously blue' were collapsed into a single 'correct source' response.

Averaged separately across the rhythmic and arrhythmic blocks, a one-tailed paired *t*-test showed that the proportion of correct source responses was significantly greater in the arrhythmic condition than the rhythmic condition, *t*(30) = 1.76, *p* = .045, *d* = .315.

Table 3.

Proportion of Correct Source judgements and the corresponding Response Time (RT) in milliseconds (ms) in the Rhythmic and Arrhythmic blocks.

	Rhythmic blocks Mean (SD)	Arrhythmic blocks Mean (SD)
Proportion of Source Correct	0.65 (0.16)	0.67 (0.14)
RT Source Correct	918 (509)	978 (526)

Seven out of the 31 participants reported awareness of temporal differences in presentation timings between blocks in the detection task. d' scores for item recognition for these seven participants were 2.37 in the rhythmic condition and 2.77 in the arrhythmic condition. The proportion of correct source judgements for these seven participants were 0.69 and 0.70 in the rhythmic and arrhythmic conditions, respectively.

EEG results

Encoding analysis - Dm effect:

The Dm effect refers to the differences due to subsequent memory and usually compares Hits versus Misses and compares the mean amplitudes in the 400-800ms time interval. In the pre-registration submission we specified that we needed a minimum of 23 participants with at least 20 hits and 20 misses per condition to be included in this analysis. However, although all 31 participants achieved more than 20 Hits per condition, only 18 participants achieved more than 20 Misses per condition (Table 4). Therefore, for the encoding analysis the mean amplitudes of the rhythmic and arrhythmic conditions were compared instead, as per Jones and Ward (2019).

For source memory encoding analysis, a subset of 23 respondents were analysed based on those who achieved at least 20 source correct trials and 20 source incorrect trials per condition (Table 4).

Table 4.

Number of participants achieving a minimum of 20 trials for each measure used in the EEG analysis.

	Hits	Misses	Correct Rejections	Source Correct	Source Incorrect
Rhythmic condition	31	19	31	30	27
Arrhythmic condition	31	19	31	31	25
Across both conditions	31	18	31	30	23

Dm effect – Rhythmic vs Arrhythmic items

The mean amplitudes in the 400-800 ms time interval were analysed using a 2 x 2 x 2 ANOVA with factors of Temporal Condition (rhythmic, arrhythmic), Image Type (object, checkerboard) and Electrode (PO7, PO8).

No effect was found for Temporal Condition ($F(1,30) = .00$, $p = .998$, $\eta_p^2 < .001$), Image Type ($F(1,30) = 1.98$, $p = .170$, $\eta_p^2 = .062$) or Electrode ($F(1,30) = .22$, $p = .641$, $\eta_p^2 = .007$). Similarly, there was no effect for two-way interactions Temporal Condition*Image Type ($F(1,30) = 3.55$, $p = .069$, $\eta_p^2 = .106$), Temporal Condition*Electrode ($F(1,30) = 3.11$, $p = .088$, $\eta_p^2 = .094$), Image Type*Electrode ($F(1,30) = 1.23$, $p = .277$, $\eta_p^2 = .039$), nor the three way interaction Temporal Condition*Image Type*Electrode ($F(1,30) = .08$, $p = .777$, $\eta_p^2 = .003$). To summarise, the temporal condition, object type or electrode did not significantly affect the Dm (Figure 6).

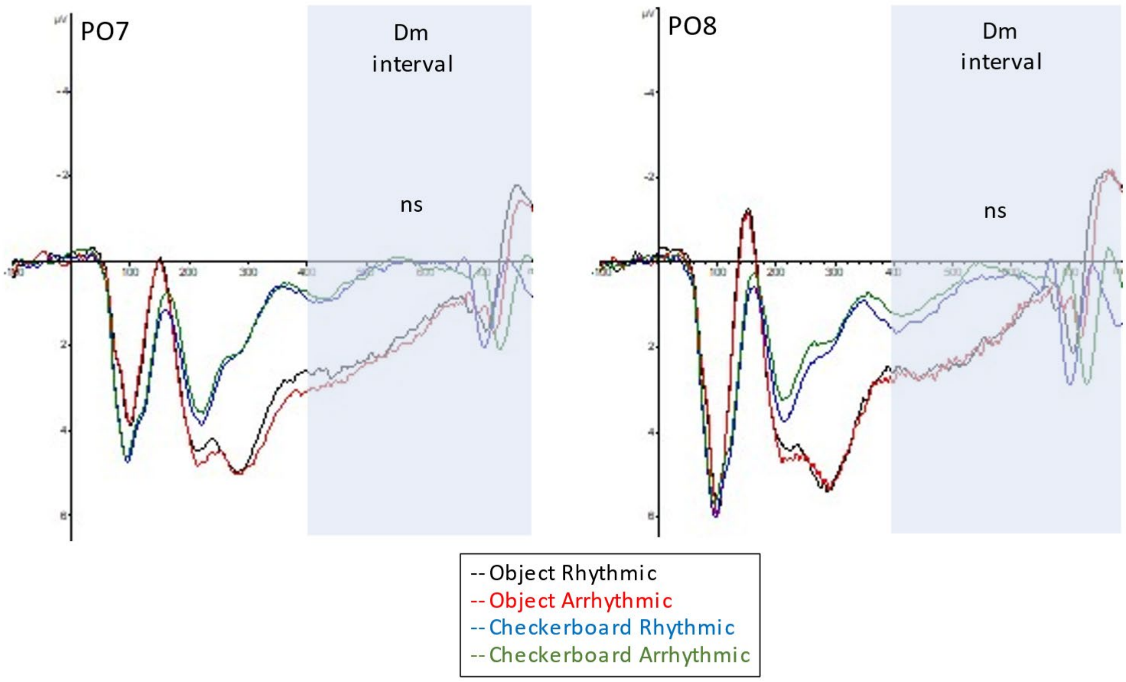


Figure 6. *Grand Averaged ERP waveforms during the encoding phase comparing objects and checkerboards in both the rhythmic and the arrhythmic conditions*.

Note. This figure shows ERPs from the PO7 and PO8 electrodes during the encoding phase. The y-axis scale is amplitude in microvolts (µV) and the x-axis is time in milliseconds (ms). Item onset is at 0ms. Objects in the rhythmic condition are represented with a black line, objects in the arrhythmic condition are represented with a red line, checkerboards in the rhythmic condition are represented with a blue line and checkerboards in the arrhythmic condition are represented with a green line. ns = non-significant effect.

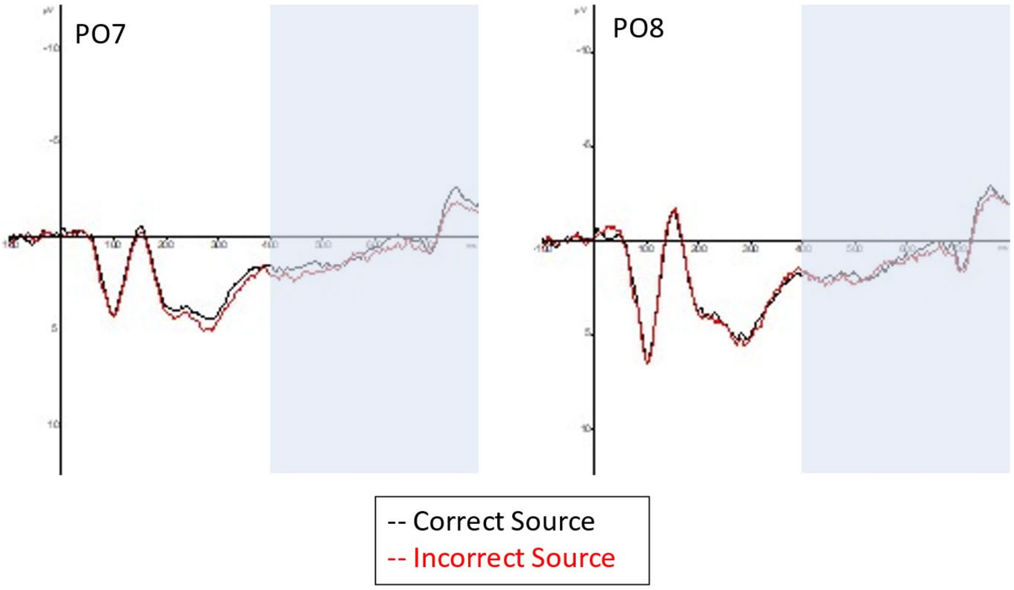
Dm effect – Source memory

The mean amplitudes in the 400-800ms time interval analysed using a 2 x 2 x 2 ANOVA with factors of Temporal Condition (rhythmic, arrhythmic), Subsequent Source Response (source correct, source incorrect) and Electrode (PO7, PO8).

No effect was found for the Dm effect for source memory. That is, no effect was found for Temporal Condition ($F(1,22) = .56$, $p = .461$, $\eta_p^2 = .025$), Subsequent Source Response ($F(1,22) = 3.18$, $p = .088$,

η_p^2 = .126) or Electrode (*F*(1,22) = .15, *p* = .701, η_p^2 = .007), nor two-way interactions Temporal Condition*Source: *F*(1,22) = .03, *p* = .859, η_p^2 = .001, Temporal Condition*Electrode (*F*(1,22) = .12, *p* = .734, η_p^2 = .005) or Source*Electrode: *F*(1,22) = .03, *p* = .877, η_p^2 = .001, nor the three-way interaction Temporal Condition*Source*Electrode (*F*(1,22) = .66, *p* = .426, η_p^2 = .029). Overall, the Dm effect was not affected by temporal condition, subsequent source response or electrode. (Figure 7)

Rhythmic – Dm effect



Arrhythmic – Dm effect

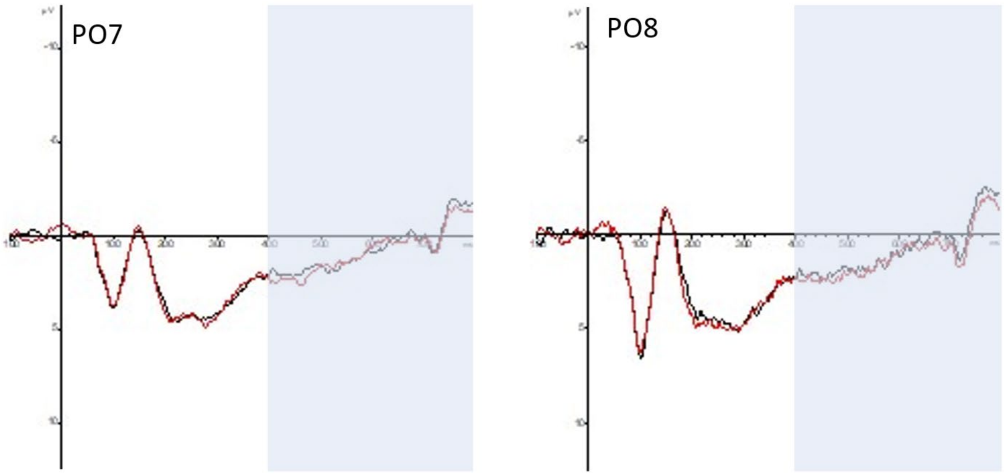


Figure 7. *Grand Averaged ERP waveforms during the Dm time interval in the encoding phase comparing items where the border colour was subsequently correctly identified (correct source) in the recognition phase to items where the border colour was subsequently incorrectly identified (incorrect source).*

Note. The top row (l-r) shows the ERPs from the PO7 and PO8 electrodes in the Rhythmic condition during the encoding phase. The bottom row shows the same components for the Arrhythmic condition during the encoding phase. The y-axis scale is amplitude in microvolts (µV) and the x-axis is time in milliseconds (ms). Item onset is at 0ms. Source correct is represented with a black line and source incorrect is represented with a red line. ns = non-significant effect.

Recognition analysis - ERP analysis of recognition components, FN400, LPC and LFE:

Recognition analysis for item memory compared Old items (hits) and New items (correct rejections) across the two temporal conditions. All 31 participants achieved more than 20 hits and 20 correction rejections in each condition. Therefore, the full cohort of 31 was used for item recognition EEG analysis.

As per the Dm effect analysis for source memory, a subset of 23 respondents were analysed for source memory EEG analysis during the recognition phase.

FN400 – Item memory

Mean amplitudes were compared for correctly identified ‘old’ items (hits) and correctly identified new items (correct rejections) at the mid frontal Fz electrode in the 300-500ms time interval. The mean amplitudes were analysed using a 2 x 2 ANOVA, with factors of Temporal Condition (rhythmic, arrhythmic) and Item Type (hits, correct rejections).

A significant effect of Item Type was found ($F(1,30) = 47.31$, $p < .001$, $\eta_p^2 = .612$), whereby old items (hits) showed a more positive mean amplitude ($M = -1.51\mu V$, SEM =.36 µV) compared to new items (correct rejections) ($M = -2.31\mu V$, SEM = .33µV) (see left hand charts in Figure 8). No effect was found for Temporal Condition (*F*(1,30) = 1.97, *p* = .171, η_p^2 = .062) nor the Temporal Condition*Item Type interaction (*F*(1,30) = .38, *p* = .543, η_p^2 = .012). To summarise, the item memory FN400 was not affected by temporal condition.

LPC – Item memory

Mean amplitudes were compared for correctly identified 'old' items (hits) and correctly identified 'new' items (correct rejections) at the left parietal P3 electrode in the 500-800ms time interval. The mean amplitudes were analysed using a 2 x 2 ANOVA, with factors of Temporal Condition (rhythmic, arrhythmic) and Item Type (hits, correct rejections).

A significant effect of Item Type was found (*F*(1,30) = 9.93, *p* = .004, η_p^2 = .249) whereby old items (Hits) showed a more positive mean amplitude (*M* = 2.64µV, *SEM* =.36µV) compared to new items (Correct Rejections) (*M* = 2.14µV, *SEM* = .35µV) (see middle charts in Figure 8). No effect was found for Temporal Condition (*F*(1,30) = 2.71, *p* = .110, η_p^2 = .083), nor Temporal Condition*Item Type interaction (*F*(1,30) = .15, *p* = .702, η_p^2 = .005). To summarise, the item memory LPC was not affected by temporal condition.

LFE – Item memory

Mean amplitudes were compared for correctly identified 'old' items (hits) and correctly identified 'new' items (correct rejections) at the frontal F2 electrode in the 800-1000ms time interval. The mean amplitudes were analysed using a 2 x 2 ANOVA, with factors of Temporal Condition (rhythmic, arrhythmic) and Item Type (hits, correct rejections). No effect found was found for Temporal Condition (*F*(1,30) = .73, *p* = .399, η_p^2 = .024) or Item Type (*F*(1,30) = 1.12, *p* = .299, η_p^2 = .036), nor the Temporal Condition *Item Type interaction (*F*(1,30) = .00, *p* = .984, η_p^2 <.001). To summarise, the item memory LFE was not affected by temporal condition nor item type.

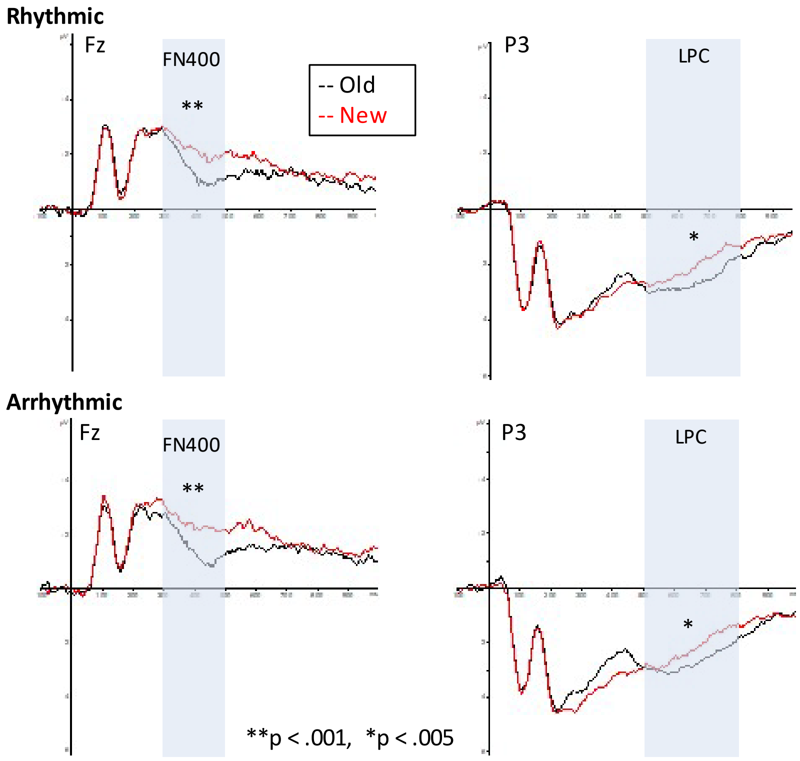


Figure 8. *Grand Averaged ERP waveforms for Old (hits) and New (correct rejections) items during the recognition phase.*

Note. The top row (l-r) shows the ERPs from the Fz, P3 and F2 electrodes for the FN400, LPC and LFE components respectively in the Rhythmic condition. The bottom row shows the same components for the Arrhythmic condition. The y-axis scale is amplitude in microvolts (µV) and the x-axis is time in milliseconds (ms). Item onset is at 0ms. Old items (hits) are represented with a black line and New items (correct rejections) are represented with a red line. The asterisks indicate a significant old/new effect for the FN400 and LPC for both items presented rhythmically and items presented arrhythmically during encoding. ns = non-significant effect.

FN400 – Source memory

Mean amplitudes were compared for source accuracy (source correct and source incorrect) at the mid frontal Fz electrode in the 300-500ms time interval. The mean amplitudes were analysed using a

2 x 2 ANOVA, with factors of Temporal Condition (rhythmic, arrhythmic) and Source Response (correct, incorrect). No effect was found for Temporal Condition (*F*(1,22) = .00, *p* = .985, η_p^2 <.001), Source Response (*F*(1,22) = .02, *p* = .885, η_p^2 = .001) nor Temporal Condition*Source Response interaction (*F*(1,22) = .00, *p* = .969, η_p^2 <.001). To summarise, no FN400 old/new effect was seen for source memory and this was the case for both rhythmic and arrhythmic encoding conditions.

LPC – Source memory

Mean amplitudes were compared for source accuracy (source correct and source incorrect) at the left parietal P3 electrode in the 500-800ms time interval. The mean amplitudes were analysed using a 2 x 2 ANOVA, with factors of Temporal Condition (rhythmic, arrhythmic) and Source Response (correct, incorrect). No effect was found for Temporal Condition (*F*(1,22) = .00, *p* = .960, η_p^2 <.001), Source Response (*F*(1,22) = 2.09, *p* = .163, η_p^2 = .087) nor Temporal Condition*Source Response interaction (*F*(1,22) = .06, *p* = .805, η_p^2 = .003). Consistent with the FN400, no LPC old/new effect was seen for source memory and this was the case for both rhythmic and arrhythmic encoding conditions.

LFE – Source memory

Mean amplitudes were compared for source accuracy (source correct and source incorrect) at the frontal F2 electrode in the 800-1000ms time interval. The mean amplitudes were analysed using a 2 x 2 ANOVA, with factors of Temporal Condition (rhythmic, arrhythmic) and Source Response (correct, incorrect). No effect was found for Temporal Condition (*F*(1,22) = 2.42, *p* = .134, η_p^2 = .099), Source Response (*F*(1,22) = .71, *p* = .409, η_p^2 = .031) nor Temporal Condition*Source Response interaction (*F*(1,22) = .00, *p* = .971, η_p^2 <.001). As per the FN400 and LPC, no LFE old/new effect was seen for source memory and this was the case for both rhythmic and arrhythmic encoding conditions.

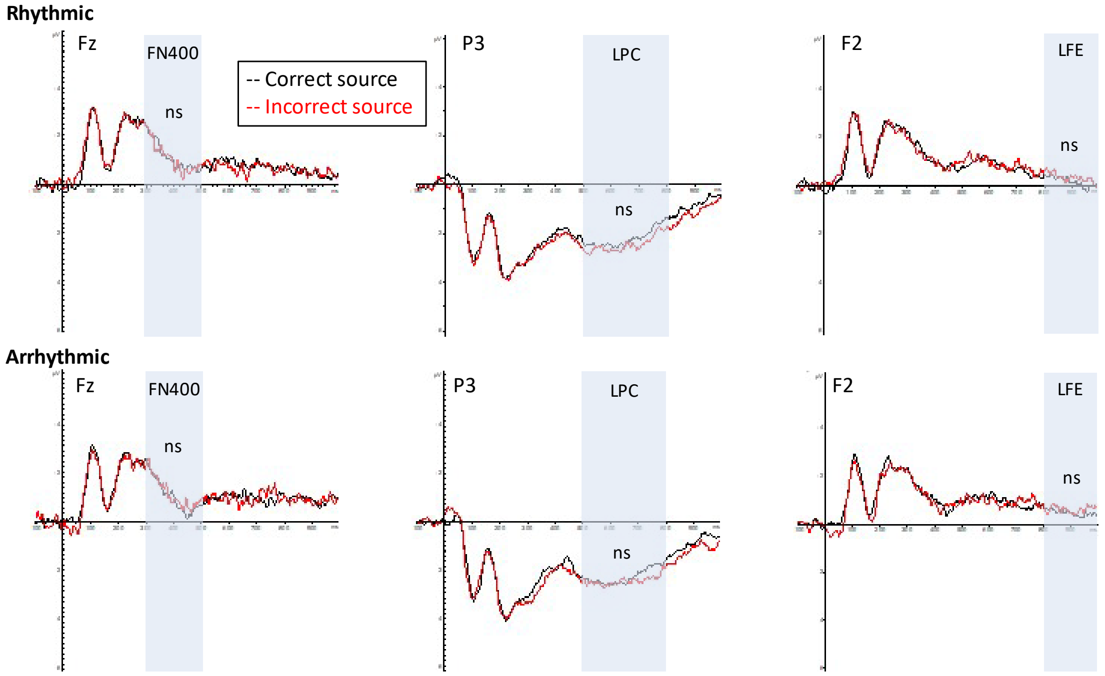


Figure 9. *Grand Averaged ERP waveforms during the recognition phase for items where the border colour was correctly identified (correct source) compared to where the border colours was incorrectly identified (incorrect source).*

Note. The top row (l-r) shows the ERPs from the Fz, P3 and F2 electrodes for the FN400, LPC and LFE components respectively in the Rhythmic condition. The bottom row shows the same components for the Arrhythmic condition. The y-axis scale is amplitude in microvolts (µV) and the x-axis is time in milliseconds (ms). Item onset is at 0ms. Source correct is represented with a black line and source incorrect is represented with a red line. ns = non-significant effect.

Discussion

This study found that temporal condition had no effect on item recognition. Likewise, temporal condition had no effect on ERP components at encoding or retrieval. For item memory, the two old/new effect ERPs that have been studied in relation to retrieval (the FN400 old/new effect and the LPC old/new effect) were present in both the rhythmic and the arrhythmic encoding conditions. This replicates the typical effect for these two ERP components for old and new items, confirming that the participants engaged in the encoding and retrieval tasks properly. No old/new effects were seen for the LFE (which has been associated with effortful retrieval or post retrieval monitoring) in either temporal condition. In Jones and Ward (2019), which this study aimed to replicate, the FN400 old/new effect was present in both rhythmic and arrhythmic conditions which is consistent with this the findings in this study. Likewise, Jones et al. (2022) found that the FN400 old/new effect was not impacted by temporal or attentional conditions at encoding. However, in Jones and Ward (2019) the LPC old/new effect was present in the rhythmic condition only whereas in the current study this component was present in both temporal conditions. Jones and Ward (2019) suggest the presence of the LPC in the rhythmic condition indicates that rhythmic presentation is associated with deeper or recollection-based processing, but the current study suggests that this association may not be present when participants are required to encode source information. The findings for the LPC in this study showed some similarities with the Jones et al. (2022) study where they also found that the LPC old new/effect was present in both the rhythmic and arrhythmic conditions but only for attended items. Whereas for unattended items there was no LPC old/new effect in either temporal condition. This suggests that the LPC may be sensitive to attention focus (as reflected in Jones et al., 2022) or perhaps is required where there is an increase in information to process or more attentional resources required (as reflected in the current study where participants were required to process both item and source information). The requirement to memorise both item and source information could also mean that attention was divided, which may have impacted subsequent item memory. This was found in the study by Troyer and Craik (2000) who found that dividing attention at encoding resulted in lower memory performance compared to full attention at encoding. One possibility is that perhaps rhythm only encourages deeper/recollection-based processing under certain task conditions.

In terms of source memory, no old/new effects were seen for the FN400, LPC or LFE when correct source and incorrect source responses were compared. However, source accuracy was significantly higher in the arrhythmic encoding condition, compared to the rhythmic encoding condition. This was the opposite of what we had predicted, as we expected that benefits of the rhythmic encoding condition seen in Jones and Ward (2019) and Jones et al. (2022) would extend to source memory accuracy. The present findings suggest that, counterintuitively, perhaps arrhythmic presentation is beneficial to the processes involved in encoding source information, or that rhythmic presentation may be detrimental to source memory. However, the ERP analyses in this study provided no clues as to why this might be.

The behavioural findings for item memory in this study differ to those seen in Thavabalasingham et al. (2016), Jones and Ward (2019) and Jones et al. (2022). Thavabalasingham et al. (2016) found that the structural presentation of items during encoding resulted in higher recognition accuracy compared to unstructured presentation and Jones and Ward (2019) found that rhythmic presentation resulted in significantly higher recognition accuracy compared to arrhythmic presentation, along with distinct neural processes in each condition. Both these studies provide support for the influence of temporal expectation on memory and the Dynamic Attending Theory (DAT) as proposed by Large and Jones (1999). However, the present study does not provide any evidence to suggest that temporal expectation provides a benefit to either item or source memory. Therefore, it is not possible to draw any conclusions from the results of this study about whether attention was enhanced by the presence of a rhythm or to suggest that phase-locking entrainment could have occurred. If a benefit of rhythm had been shown in the behavioural results in this study then it may have been of interest to carry out some exploratory analysis to look at the phase locking factor to see if this could provide support for the DAT. However, even if this had been done it would be very difficult to distinguish between a stimulus evoked response versus phase resetting.

There have been other studies on recognition memory which also found no effect of presentation timing on subsequent item recognition. In a study by Kulkarni and Hannula (2021) participants were presented with images of common objects at encoding which used a similar timing structure to the one used in by Thavabalasingham et al. (2016), whereby images were grouped into mini-sequences of four and each mini-sequence was presented twice in succession. The aim of the study was to investigate subsequent recognition for specific detail of these items when they were encoded either under structured temporal conditions or under unstructured temporal conditions. The timing between the images was manipulated via the inter-stimulus interval (ISI); where in the structured condition each image set followed the same regular fixed timing pattern for each repetition, in the unstructured condition these timings were pseudo-shuffled so that the timing pattern differed between the repetitions. At test, old items were presented again, along with an equal number of perceptually similar lures (categorised as either high similarity or low similarity) and an equal number of new items. Participants had to respond whether the object was old, similar or new. The lures were included as participants would need to encode detailed representations of the items in order to successfully distinguish between old items and lures. In contrast to the Thavabalasingham et al. (2016) study they found that there were no significant differences in item recognition between the temporally structured and temporally unstructured conditions. This suggests that the benefits of temporally predictive image onset on memory does not extend to memory where participants are required to encode specific detailed information about the item and may partly explain the null effects found for item recognition in our current study. That is, the benefits of rhythmic or structured presentation timing may only impact memory tasks where participants are not required to encode specific perceptual or contextual details. However, this explanation may not go far enough, as when Kulkarni and Hannula (2021) aimed to exactly replicate the study by Thavabalasingham et al. (2016), by using identical materials and procedures they were again unable to reproduce the beneficial effect of structured presentation timing on subsequent recognition. They suggested that this may because the effect of temporal expectation on subsequent memory could be very subtle and sensitive to minor changes, and that this theory is supported by the small effect sizes seen both for Thavabalasingham et al. (2016) and Jones and Ward (2019). Overall, the null effects of temporal conditions in both the current study and the findings by Kulkarni and Hannula (2021) suggest that any benefits of temporally predictive presentation may be limited.

It could be argued that a difference in paradigm between the studies could contribute to these limitations and why the results from previous studies (Thavabalasingham et al., 2016; Jones & Ward, 2019; Jones et al., 2022) were not replicated. However, care was taken during set up to ensure that the current study matched the Jones and Ward (2019) study in terms of design and stimuli used, with the purpose of examining whether the current study could replicate the results found in Jones and Ward (2019) (as seen in the replication of these findings in Jones et al., 2022). Despite this, there were still a number of differences between the current study and the Jones and Ward (2019) study that could not be avoided. Firstly, the response options during the test phase were different. In Jones and Ward (2019) a six-point confidence scale was used, therefore the participants had six options to choose from, whereas in the current study there were only three options. Potentially this could have triggered a slightly different retrieval / evaluation process which may or may not have been influenced by temporal structure during encoding. Another difference in the current experiment compared to Jones and Ward (2019) is that while the objects themselves were unchanged between study and test, the context in which they were presented differed, i.e., during the study phase the items were presented with either a cyan or magenta border, whereas in the test phase there was no border on any of the items. Whereas, in Jones and Ward (2019) the images were identical between study phase and test phase as no border was used. Tulving (1968) proposed that memory is generally better for recognition tests rather than recall due to the overlap of information at encoding and retrieval and the Jones and Ward (2019) study would have had a greater overlap between encoding and retrieval due to the nature of the study design. This is seen in the proportion of Hits minus False Alarms which was higher in the Jones and Ward (2019) study (0.77 for rhythmic and 0.74 for arrhythmic) whereas this was slightly lower in the current study (0.67 and 0.68 for rhythmic and arrhythmic respectively).

At the end of the experiment anecdotal feedback from some participants reported that they tried to use a strategy during the study phase to try to help them remember the images and their associated border colour – for example that they focussed just on memorising the blue images so that they could rely on familiarity for the pink images, or some said they tried to attach a meaning between the colour and the object to help them remember it. However, most of those saying they used a strategy felt it was hard to maintain throughout the experiment. These strategies could have enhanced the depth of processing in this experiment by applying semantic meaning or top down processes to create an association between the item and colour which may not have been utilised in Jones and Ward (2019) where the only requirement was to memorise the images. Thus, the participants in the Jones and Ward (2019) study possibly relied on shallow / familiarity-based processing rather than the deeper / semantic based processing that might be required to remember source information. It is possible that rhythmic presentation could be beneficial for shallow / familiarity-based processing and not for deeper processing. However, further research is needed as this clashes somewhat with the explanation that the difference in neural components seen for rhythmic items compared to arrhythmic items (i.e., greater Dm effect and the presence of LPC in rhythmic condition) in Jones and Ward (2019) reflected deeper processing leading to greater item memory accuracy. Given this was only spontaneous anecdotal feedback from a handful of participants, rather than collected in a consistent and reliable manner we do not know how many of our sample used some form of strategy to help them memorise the items and background colour, nor the exact details on the type of strategy used. The type of strategies used could have varied considerably between participants i.e., in terms of the depth of processing used, and there is no reliable way of measuring this. It is also unknown whether any strategies were used in Jones and Ward (2019) study so we can only speculate that source memory tasks may be more likely to encourage use of strategies due to an increased amount of information participants are required to try and memorise.

Given that the source information in the current study was extrinsic to the item rather than intrinsic it may have meant the source information had to be processed separately, perhaps relying more on deeper or recollection-based processes, rather than processed as a unitised item and using shallower / familiarity-based processes. In contrast, it could be argued that the study design did not encourage deeper or recollection based processing, i.e., border colour may not have encouraged the semantic analysis that could be required for deeper processing as it was separate from the item. Equally the participants were not explicitly instructed to think of the relationship between the item and the colour (although as mentioned above some anecdotal feedback suggests some may have explicitly attempted to use this strategy). Diana et al. (2011) found that the computed familiarity estimate was higher for highly unitised words and colours. Kuo and Van Petten (2006) also found that item accuracy and source accuracy were found to be correlated in the colour congruency task encoding condition, but no correlation was found in the size judgement condition. This suggests that source information may be integrated into item memory at encoding which may utilise familiarity-based processes at retrieval. Further research is required to understand the impact of temporal condition on unitised or intrinsic source information which may shed light on the processes involved.

Other evidence that may point to different processes or type of memory used in this test compared to Jones and Ward (2019) and Jones et al. (2022) were response times. During the study phase detection of targets was slower in the current study (mean = 576ms for rhythmic and mean = 573ms for arrhythmic) compared to Jones and Ward (2019) (mean = 485ms for rhythmic and mean = 526ms for arrhythmic) and Jones et al. (2022) (mean = 529ms for rhythmic and mean = 550ms for arrhythmic). These timings may relate to the amount of information participants were required to attend to in each experiment. The Jones and Ward (2019) experiment, in which participants had to attend to the objects only, had the fastest response times. In Jones et al., (2022) there were two items presented at a time, and while only one of these items was ever an object (and the other was a checkerboard) and they were cued to only attend to either the left- or right- hand stream of images there was still more information to process than in the 2019 study. Therefore, this may have resulted in the slightly slower response times. The current experiment arguably had the most information that the participants were required to attend to, i.e., they had to attend to both the object as well as the border colour, which may have influenced the slower response times to targets.

There were also less erroneous responses to targets in the current study compared to both Jones and Ward (2019) and Jones et al. (2022). This suggests that participants perhaps were paying closer attention to the images (in order to encode both the object and the border colour) which could point to different/deeper processes being utilised this time around. Guo et al. (2006) also found that target detection was slower in the source test (where participants were required in the test phase to determine for each item whether it was old-previously presented on a circle, old-previously presented on a square, or a new item) compared to the item test (where participants were not required to remember the source and just had to respond whether it was old or new). They suggest this is because demands may have been higher in the encoding phase of the source test compared to the item test as participants were required to encode the background information as well as the item. However, they also found that target detection was also less accurate in the source test compared to the item test, whereas target detection accuracy does not appear to differ much from that seen in Jones and Ward (2019). At retrieval the reaction times for Hits were slower in the current study compared to Jones and Ward, although Misses and Correct Rejections were faster in the current study. Ecker et al. (2007) also found that reaction times in the test phase were significantly slower in the extrinsic condition (border colour) compared to the intrinsic condition (item colour) suggesting that the retrieval of intrinsic details is perhaps more automatic or based on a familiarity-based process whereas retrieval of extrinsic details is a slower / recollection-based process. Diana et al. (2011) also found that when source information is unitised with the item at encoding the behavioural data appears to show more familiarity / shallow based processing. In the current study there was no relationship between the item and source colour and participants were not instructed to think about the relationship between the two.

However, the above does not fully explain why greater source accuracy was observed in the arrhythmic than the rhythmic condition. It is possible that more effortful encoding is required during arrhythmic presentation as you are unable tune in to the rhythm to make processing more habitual / less effortful. There is lower expectation of when the item is likely to appear in the arrhythmic condition, therefore this could heighten attention when it does appear. There is an evolutionary advantage to being aware of unexpected or novel information, as being able to discern between familiar and unfamiliar stimuli to allow a faster and more accurate response to a potential danger in the environment.

Conclusion

In conclusion, we found no impact of temporal condition on item memory accuracy or any of the memory specific ERPs. These findings differ to those that were found in the studies which used the same images and temporal structure (i.e., Jones & Ward, 2019; Jones et al., 2022) which found that item memory accuracy was greater for rhythmic encoding conditions. In addition, we found that source accuracy was greater in the arrhythmic condition which was the opposite to what we had predicted. These findings suggest that further research is needed, to determine whether temporal expectations are perhaps only beneficial to item memory / or simpler tasks that may require different types of processing, or whether the benefits of rhythmic / structured presentation could extend to any other types of memory. For example, differences have been shown for source accuracy between conditions where source information is highly unitised with the item (Diana et al., 2011), or where participants were explicitly instructed to think about the relationship between the source and the item (Kuo & Van Petten, 2006). Understanding the impact of temporal condition when the source is unitised / or semantically processed could help further understand the mechanisms and limitations of rhythmic presentation of stimuli. Similarly, further understanding the impact of attention on source memory under different temporal conditions could also provide further insight into the processes used.

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