



Registered Report

Null effects of temporal prediction on recognition memory but evidence for differential neural activity at encoding. A registered report[☆]



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ARTICLE INFO

Article history:

Protocol received: 20 March 2020

Protocol approved: 4 September 2020

Received 25 May 2023

Reviewed 27 July 2023

Revised 21 August 2023

Accepted 26 September 2023

Action editor Robert D. McIntosh

Published online 4 October 2023

Keywords:

Temporal expectation

Prediction

Rhythm

Recognition memory

EEG

ABSTRACT

Previous research has demonstrated that rhythmic presentation of stimuli during encoding boosts subsequent recognition and is associated with distinct neural activity compared with when stimuli are presented in an arrhythmic manner. However, it is unclear whether the effect is driven by automatic entrainment to rhythm or non-rhythmic temporal prediction. This registered report presents an Electroencephalographic (EEG) study aimed at establishing the cognitive and neural mechanisms of the effect of temporal prediction on recognition. In a blocked design, stimulus onset during encoding was systematically manipulated in four conditions prior to recognition testing: rhythmic fixed (RF), rhythmic variable (RV), arrhythmic fixed (AF), and arrhythmic variable (AV). By orthogonally varying rhythm and temporal position we were able to assess their independent contributions to recognition enhancement. Our behavioural results did not replicate previous findings that show a difference in recognition memory based on temporal predictability at encoding. However, event-related potential (ERP) component analysis did show an early (N1) interaction effect of temporal position and rhythm, and later (N2 and Dm) effects driven by temporal position only. Taken together, we observed effects of temporal prediction at encoding, but these differences did not translate to later effects of memory, suggesting that effects of temporal prediction on recognition are less robust than previously thought.

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[☆] Accepted Stage 1 manuscript available here: <https://osf.io/f8c6g/>.

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1. Introduction

The way in which information is processed during encoding influences subsequent memory. New evidence suggests that temporal prediction – the anticipation that an event will occur at a particular point in time – plays a key role in memory formation (see Jones & Ward, 2019; Thavabalasingam, O’Neil, Zeng, & Lee, 2016), but little is known about the conditions under which this occurs, or the underlying mechanisms.

Presenting stimuli in a temporally structured or rhythmic manner facilitates perception, leading to improved decision times (Martin et al., 2005), detection thresholds (Herrmann, Henry, Haegens, & Obleser, 2016; Lawrance, Harper, Cooke, & Schnupp, 2014) and perceptual discrimination (Rohenkohl & Nobre, 2011; for reviews see, Haegens & Zion Golumbic, 2018; VanRullen, 2016). We (Jones & Ward, 2019) recently reported evidence that recognition memory – the capacity to judge whether a specific item has been presented before in a particular context – is affected by the rhythmic presentation of stimuli during encoding. Participants were exposed to a continuous stream of everyday objects and checkerboards during a series of encoding blocks with rhythmic versus arrhythmic stimulus onset timings. Stimuli were presented for an equal duration in both conditions, but the inter-stimulus interval (ISI) was manipulated. During rhythmic blocks the ISI was fixed, generating a constant rhythm. This form of stimuli presentation is often referred to as an isochronous rhythm, generating temporal prediction based on periodic presentation of stimuli (Rimmele, Morillon, Poeppel, & Arnal, 2018). In the arrhythmic blocks, the ISI was randomly generated from a range where the mean ISI was the same as that in the rhythmic blocks. Subsequent recognition was greater for objects encoded in rhythmic blocks compared to those in arrhythmic blocks, and this was despite a general lack of awareness in participants about the temporal manipulation. Electroencephalographic (EEG) recordings provided evidence for differential neural activity as reflected in memory-specific ERP components: At recognition the FN400 old/new effect was unaffected by temporal structure, whereas the late positive component (LPC) old/new effect was observed only for rhythmically encoded items. This suggests that the effects of temporal structure at recognition are characterised by strength of encoding.

Other recent studies have reported effects of rhythm on memory. Johndro, Jacobs, Patel, and Race (2019) reported greater recognition of nonverbal stimuli (faces) that were presented in synchrony with a rhythmic auditory background beat during encoding. In a similar design, Hickey, Merseal, Patel, and Race (2020) reported that enhanced neural tracking was associated with greater recognition of images of everyday objects that appeared in-synchrony with an auditory background beat, compared to those that appeared out-of-synchrony. Moreover, Clouter, Shapiro, and Hanslmayr (2017) also showed that associative memory depends upon the timing synchrony between different sensory cortices. In their study, memory for sound-movie clip pairs was greater when luminance and amplitude adjustments were synchronous rather than out of phase (see also, Wang, Clouter, Chen, Shapiro, & Hanslmayr, 2018). As such, there is wide potential

application in the use of rhythm as a tool for memory improvement.

Rhythm appears to bolster encoding in the absence of awareness. Participants in Jones and Ward (2019) were largely unaware of the rhythmic versus arrhythmic presentation timings, and other studies also report a general lack of awareness in participants of temporal manipulations (e.g., Thavabalasingam et al., 2016; van de Ven, Kochs, Smulders, & De Weerd, 2017). It is therefore unlikely that greater recognition following rhythmic than arrhythmic encoding can be explained by participants adopting different strategies and may suggest an implicit mechanism. One possibility concerns the Dynamic Attending Theory (DAT; Large & Jones, 1999). The DAT proposes that rhythms automatically entrain peaks of heightened attention that modulate the gain of sensory input, which provides a benefit to the processing of stimuli presented at attended peaks – that is, those appearing in time with the rhythm. This is in line with evidence that intrinsic brain oscillations entrain to ongoing external rhythms, aligning the firing pattern of neural populations such that stimuli presented in phase are at a processing advantage compared with those presented out of phase (Arnal & Giraud, 2012; Calderone, Lakatos, Butler, & Castellanos, 2014; Henry & Herrmann, 2014; Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008). Interestingly, Jones and Ward (2019) compared ERPs locked to objects encoded during rhythmic compared to arrhythmic presentations and showed no difference of early perceptual components but clear differences in later cognitive components. This suggests that entrainment to periodic stimulation might not modulate the gain of sensory input but affect later post-perceptual processing of stimuli (see also Lakatos, Gross, & Thut, 2019, for an in-depth discussion on entrainment).

Entraining to periodic sensory input is only one of several ways to generate temporal predictions. Temporal predictions can be inferred from heterochronous stream of events such as a gradual change in tempo (Cope, Grube, & Griffiths, 2012), symbolic cues, such as knowing an amber traffic light will shortly turn green, or hazard functions which are probability based predictions with increasing likelihood of an event occurring as time passes if it has not yet happened (Nobre & van Ede, 2018). Increasing temporal prediction has been shown to facilitate response times (Ivan Griffin, Miniussi, & Nobre, 2001; Lange & Röder, 2006; Pomper, Keil, Foxe, & Senkowski, 2015), improve perceptual discrimination (Correa, Lupiáñez, & Tudela, 2005; Rohenkohl, Gould, Pessoa, & Nobre, 2014) and enhance neural processing for predicted over unpredicted targets (Buhusi & Meck, 2005; Correa, Lupiáñez, Madrid, & Tudela, 2006; Rohenkohl & Nobre, 2011; Zanto et al., 2011). Temporal predictions can also be generated by aperiodic stimulus streams creating temporal regularities (Morillon, Schroeder, Wyart, & Arnal, 2016; Rimmele et al., 2018). Thavabalasingam et al. (2016) reported enhanced recognition following the presentation of items in a fixed repeating sequence of onset timings (i.e., 100 msec, 500 msec, 1000 msec, 2000 msec) compared to random onset timings. This occurred under intentional encoding (Experiments 1 and 2), incidental encoding (Experiment 3), and regardless of whether participants were aware of the temporal manipulation. The fixed sequence of onset timings would have allowed

participants to anticipate the onset of the next item, leading to a processing advantage compared to when stimulus onset was unpredictable.

1.1. The current investigation

Temporal prediction has been shown to provide a benefit to memory following encoding of stimuli presented with both isochronous rhythm and aperiodic temporal regularities. Therefore, this study's first aim is to test whether these factors independently or collectively enhance memory. To achieve this aim, our experimental design systematically and independently manipulates the degree of temporal prediction based on rhythm and temporal position. Rhythm has often been considered as a binary phenomenon being either rhythmic or arrhythmic but of note is that many events can appear rhythmic even though they are decidedly aperiodic (Obleser, Henry, & Lakatos, 2017). Rhythm in the present study contrasts conditions with either a completely fixed periodic rhythm (also known as isochronous rhythm; predictable) with a stimulus stream where intervals between events are random which, here, we call arrhythmic (unpredictable). Temporal position refers to predicting *when* in a temporal sequence an object will appear, either at fixed (predictable) or variable (unpredictable) position in the stimulus stream. These temporal manipulations occur during the encoding phase and lead to four conditions: rhythmic fixed (RF), rhythmic variable (RV), arrhythmic fixed (AF), and arrhythmic variable (AV).

Stimuli will include the 3:1 ratio of checkerboards and images of everyday objects as in Jones and Ward (2019), and the experiment will consist of eight encoding-test blocks, two per condition. The encoding phase in each block will involve a detection task in which participants are instructed to detect animals (targets) as quickly as possible. All ISIs during encoding in the rhythmic conditions will be constant, with a stimulus (checkerboard or object) appearing every 600 msec creating an isochronous rhythm, while stimulus onset in the arrhythmic conditions will be randomly generated from a uniform distribution with a range of 70 msec–1130 msec and a mean of 600 msec. In the fixed temporal position conditions, a real object will be presented on every fourth trial, with checkerboards occurring on all other trials. In the variable temporal position conditions the order of presentation of checkerboards and real objects will be randomised with at least one checkerboard between two objects. Thus, in the RF condition participants will be able to anticipate both the onset of stimuli and the occurrence of real objects, while at the other extreme in the AV condition participants will not be able to predict stimulus onset or the occurrence of real objects. In the RV condition participants will be able to anticipate stimulus onset but not predict when a real object will occur, and vice versa in the AF condition. Participants will not be informed of the manipulations of rhythm and temporal position and will be screened for awareness at the end of the experiment. Following each encoding phase, participants will perform a recognition task in which they will judge whether or not individually presented objects were shown in the prior encoding phase (Fig. 2). The behavioural data will allow us to

determine the independent contributions of periodic rhythm and temporal regularity to recognition memory.

Our second aim is to examine differences in the processing of stimuli during encoding as a function of temporal prediction. The use of EEG will enable us to examine the amplitude and latency of the successive ERP components, to measure the time course of stimulus and cognitive processing (Luck, Woodman, & Vogel, 2000). This allows us to test whether temporal prediction generated by periodic rhythm and/or temporal position enhance early perceptual processing of stimuli. The DAT (Large & Jones, 1999) predicts temporal expectation to generate temporal windows of increased sensory gain, resulting in enhanced perceptual processing of stimuli. There is some evidence that the modulation of the N1 component, thought to reflect sensory gain (Störmer, McDonald, & Hillyard, 2009), is affected by rhythm with increased amplitude for temporally expected compared to unexpected stimuli (Escoffier, Herrmann, & Schirmer, 2015). We observed an N1 effect in Jones and Ward (2019) but with reduced amplitude for rhythmic compared to arrhythmic items. However, this effect was only present for checkerboards and not objects. A possible explanation is that this effect was in part driven by sensory suppression as the checkerboards were repeated whilst the objects were not. There is evidence to suggest that repetition suppression (due to repeating stimuli) occurs at early perceptual processing stages and expectation suppression affects mid processing stages (Todorovic & de Lange, 2012). Moreover, recent evidence points to a dissociation between N1 and N2 in expressing temporal predictability effects. Xu, Meng, Yu, Jung, and Ming (2020) observed a reduced N1 and enhanced N2 for temporally anticipated stimuli and proposed this may reflect the perceptual prediction paradox where predictable events can lead to both enhanced and suppressed perceptual effects (Press, Kok, & Yon, 2020). The exact role of temporal prediction on the N1 component is not well established, however, post-perceptual processes such as the N2 and P3 have shown particularly sensitive to temporal orienting with increased amplitude for temporally expected events (e.g., Griffin, Miniussi, & Nobre, 2002; Miniussi, Wilding, Coull, & Nobre, 1999; Rolke, Festl, & Seibold, 2016, see Correa et al., 2006 for a review). It may be that the benefits of temporal structure at recognition are primarily driven by differences at later stages of processing during encoding. That is, temporal expectancy may not influence early perceptual processing of items, but instead affect later stages associated with cognitive processing such as updating working memory (Donchin, 1981) and richer encoding (Paller & Wagner, 2002). Thus, ERP data at encoding will allow us to disentangle whether temporal prediction generated by rhythm or temporal position, or both, are associated with increased sensory gain or later processing of stimuli.

Our third aim is to explore the effect of temporal manipulations on the processing of stimuli at retrieval. To do so, we will examine ERP components locked to stimuli presentation at recognition. Two key components at recognition have been identified: the FN400 and the LPC. The FN400 old/new effect has been linked to perceptual and familiarity-based processing, while the LPC old/new effect is commonly unaffected by

familiarity but shows modulations under deeper or recollection-based processing (Rugg & Curran, 2007). Few studies have examined memory retrieval ERPs as a function of temporal manipulations, but our previous findings showed that rhythmic encoding modulated the LPC but not the FN400 (Jones & Ward, 2019). Examination of the effect of rhythm and prediction on these recognition ERP components in this study will provide further insight into how temporal manipulations at encoding affect subsequent memory.

1.2. Alternative hypotheses

Our design orthogonally manipulates rhythm and temporal position to independently assess the contribution of both on memory. We therefore set out four alternative hypotheses, as we are agnostic to the degree which each will contribute to any given dependant variable (DV). Hypotheses below and in Fig. 1 are numbered to correspond to the analyses described in the analysis pipeline – we produce separate analysis pipelines for different dependant variables. However, critically, each DV will be tested against the same hypotheses, outlined below, separately. This is precisely because the independent effects of rhythm and temporal manipulation on memory, as measured by behaviour, may be different to the effects on the ERPs at encoding or retrieval. These hypotheses outline the temporal prediction effects generated by rhythm and temporal position on behaviour and ERP components at encoding and recognition. The DV measures referred to are: 1. d' ; 2. ERP amplitudes at encoding; 3. ERP Old/New effects at retrieval.

1. If memory or ERPs are driven purely by entrainment to an external periodic rhythm, then DV measures will be greater in the rhythmic than the arrhythmic conditions, with no interaction with the additional predictive element (e.g., $RF = RV > AF = AV$) (**Hypothesis 1**)
2. If memory or ERPs are driven by non-rhythmic temporal prediction, then DV measures will be greater in the fixed

than the variable temporal position conditions, with no additional benefit of rhythm (e.g., $RF = AF > RV = AV$) (**Hypothesis 2**)

3. If memory or ERPs are driven primarily by entrainment to an external periodic rhythm but with an added benefit of fixed temporal position, then DV measures will be greatest in the rhythmic fixed condition, lowest in the arrhythmic variable condition, and greater in the rhythmic variable than the arrhythmic fixed condition (e.g., $RF > RV > AF > AV$) (**Hypothesis 3**)
4. If memory or ERPs are driven by an equal combination of temporal prediction generated by a periodic rhythm and temporal position, then DV measures will be greatest in the rhythmic fixed condition and lowest in the arrhythmic variable condition (e.g., $RF > RV = AF > AV$) (**Hypothesis 4**)
5. If memory or ERPs are unaffected by temporal manipulations then a null effect is expected and DV measures will not differ across the four conditions.

1.3. Manipulation check

The rhythmic fixed (RF) and arrhythmic variable (AV) conditions provide a key manipulation check – the former is associated with the greatest temporal prediction and should produce high levels of recognition, while the latter is associated with the least temporal predictive information and should produce the lowest recognition levels.

2. Methods

2.1. Transparency statement

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

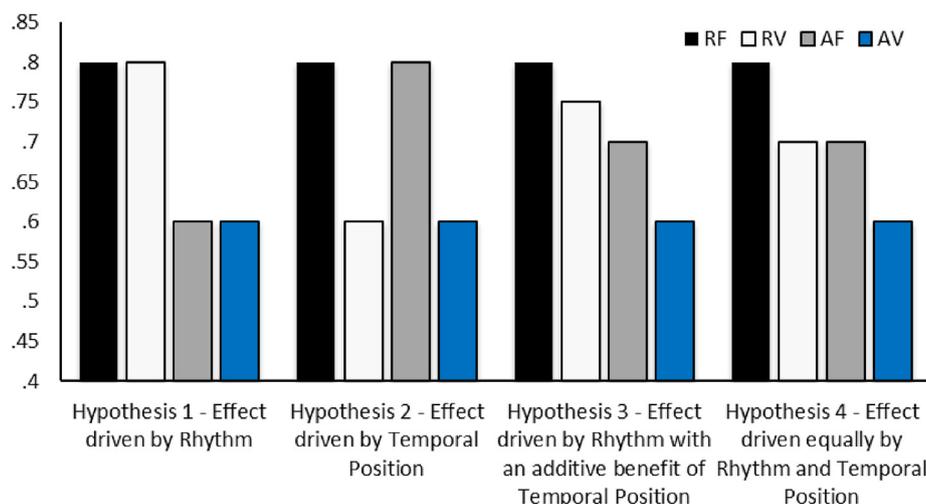


Fig. 1 – Graphical representation of the four alternative hypotheses. RF = rhythmic fixed, RV = rhythmic variable, AF = arrhythmic fixed, and AV = arrhythmic variable.

2.2. Design and participants

Participants were exposed to eight encoding-test blocks, two of each condition: rhythmic fixed (RF), rhythmic variable (RV), arrhythmic fixed (AF), arrhythmic variable (AV), in a repeating counterbalanced order: (1) RF → RV → AF → AV. (2): RV → AF → AV → RF. (3): AF → AV → RF → RV. (4): AV → RF → RV → AF.

Participants were aged between 18 and 35 years (M age = 23.44 years; SD = 4.84; 21 male), fluent in English, with normal or corrected vision. Due to the rapid presentation of objects during the encoding phases, it was a requirement that participants should not have photosensitive epilepsy. Participants were recruited through the Middlesex University online recruitment system and local advertisements. Ethical approval was granted by Middlesex University Research Ethics Committee. Participants provided written informed consent to confirm their agreement to take part and that they met the inclusion criteria. Participants were rewarded with Amazon vouchers at a rate of £9 per hour.

An a priori power analysis (G*Power) was conducted to estimate the required sample size using a medium effect size ($f = .25$) with power at .90. A 2(Rhythm) × 2(Prediction) repeated measures design was used. The non-sphericity correction was set to maximum ($1/m-1$, where m signifies the number of measurements) and a moderate correlation between measures was assumed ($r = .6$). This resulted in an estimated sample size of 54 participants with an actual power of .90. Additional participants were only tested to replace any who withdraw prior to completion of the experiment or were excluded on the following grounds: (1) failure to understand or follow task instructions (threshold detailed in analysis pipeline); (2) technical issues resulting in too few trials being available for analysis. Further details are given in the analysis pipeline. In total, nine participants were replaced to achieve the required sample size of 54 usable participants.

2.3. Stimuli

Stimuli included the images of familiar everyday objects used by Jones and Ward (2019), with additional items to accommodate the increased number of trials (this study used 8 encoding-test blocks rather than 6). In total there were 557 greyscale images of objects. Each encoding phase contained a unique set of 30 critical items plus 6 filler items as a primacy and recency buffer, randomly interspersed among 90 presentations of checkerboard, resulting in a ratio of 3:1 checkerboard to object presentations. Target items during encoding were images of animals. Between 3 and 6 targets appeared in each encoding phase (using a predefined random structure) to ensure that the number of responses remained unpredictable. The total number of targets across the experiment corresponded to 10% of object trials (29 trials). Each recognition test phase contained the 30 objects from the encoding phase immediately prior (excluding targets and primacy/recency buffers), along with 30 completely new objects. Eighteen sets of 30 critical objects were counterbalanced between participants such that each set appeared an equal number of times in each block, and an equal number of times as studied (old) or new type.

2.4. Procedure

Participants were tested individually and the duration of the experiment was approximately one and a half hours not including EEG preparation. E-Prime v.3 (Psychology Software Tools) was used to administer the experiment and record behavioural responses.

Participants were informed that the experiment consisted of eight blocks, each with two tasks: a detection task and a memory task. In the detection task participants witnessed a series of objects and checkerboards in rapid succession and were instructed to press the spacebar as quickly as possible whenever they saw an animal. They were informed that animals would appear infrequently with the number varying in each detection task. Participants were aware that their memory of the objects would be tested.

Each trial in the detection task consisted of a black central fixation cross on a white screen, followed by an object or checkerboard (Fig. 2). In all blocks, objects and checkerboards were presented for precisely 600 msec, however, the presentation of the fixation cross during the ISI differed across the rhythmic and arrhythmic conditions. Participants were not made aware of this. In the RF and RV blocks, the ISI was held constant at 600 msec, generating a rhythmic presentation of stimuli at 1.67 Hz. That is, the items (objects or checkerboards) appeared every 1200 msec, but the 1.67 Hz rhythm is defined as a change in the visual scene, every 600 msec. In the AF and AV conditions the ISI duration was randomly generated from a uniform distribution with a range of 70 msec–1130 msec and a mean of 600 msec. Thus, all events in the rhythmic conditions were constant, but stimulus onset was random in the arrhythmic conditions. The average ISI was equivalent in all conditions (600 msec), as well as the total duration of each encoding phase. The purpose of including a 3:1 ratio of checkerboards to objects was to extend the duration of the encoding phases, to create a maximally rhythmic sense of presentation in the rhythmic blocks. Additionally, twelve checkerboards were presented at the start of each encoding phase. At least one checkerboard was presented between trials containing an object. In the RF and AF conditions, a real object was presented on every fourth trial (always following three checkerboards), while in the RV and AV conditions objects and checkerboards were presented in a new random order for each participant.

Following each detection task, there was a delay of approximately 1 min prior to the recognition task, in which participants solved simple algorithmic problems and read instructions. The recognition task included the 30 critical objects from the detection task immediately prior along with 30 new items in a new random order for each participant. Participants were informed that half of the objects in this phase were shown in the detection task and half were not. On each trial, an object was presented in the centre of the screen for 800 msec, after which time the participant will be prompted to make a judgement as to whether it was shown in the detection task immediately prior. The instruction “Was this object shown in the last detection task?” and response scale “6 = sure yes, 5 = think yes, 4 = guess yes, 3 = guess no, 2 = think no, 1 = sure no” appeared below the object, and participants were required

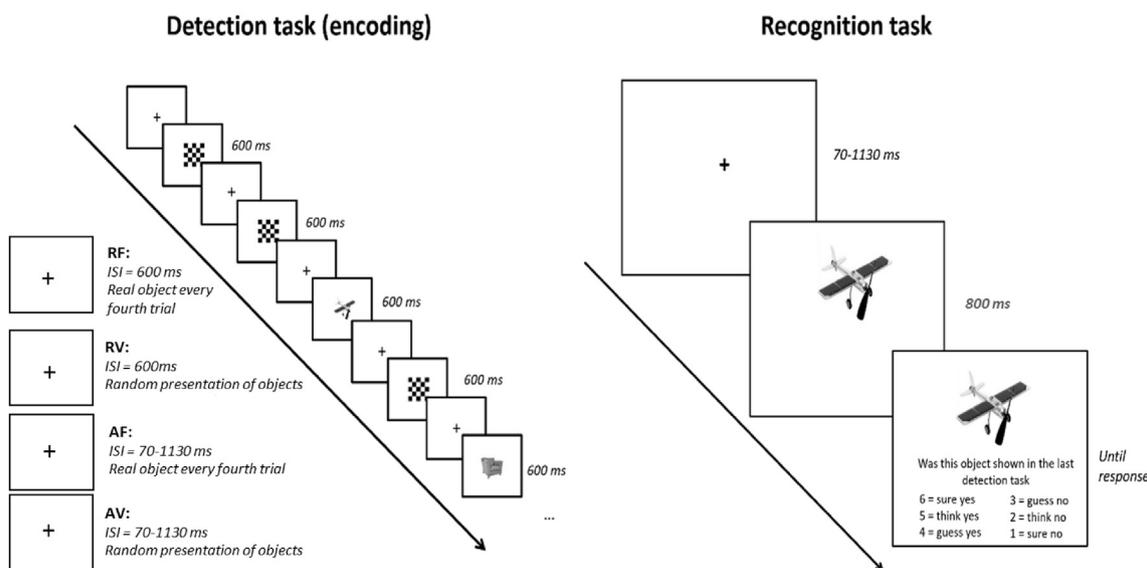


Fig. 2 – Left: Events in the detection task. Objects and checkerboards were presented for a fixed duration of 600 msec. The ISI (fixation cross) was presented for 600 msec in the RF and RV condition, for an interval randomly generated from a uniform distribution with a range of 70 msec–1130 msec and a mean of 600 msec in the AF and AV conditions. The occurrence of real objects was predictable in the RF and AF conditions (every fourth trial, separated by three checkerboards), but in the RV and AV conditions the presentation of real objects and checkerboards was variable. Right: Events in the recognition task. Each object (old or new) was presented for 800 msec after which time the participant was prompted to make a recognition judgement.

to respond via a number keypress. No time limit was imposed, and the object and response scale remained on the screen until a response was made. Finally, a central fixation cross was presented for a duration ranging between 70 and 1130 msec prior to the next trial.

Participants performed a short practice block containing 16 detection task trials with rhythmic timings (4 objects and 12 checkerboards) and 8 recognition trials (4 studied and 4 new). The experimental blocks were then presented in the predefined counterbalanced order, with a 5 min comfort break after the fourth block. On completion of the experiment, participants were probed for awareness of the temporal manipulations. They were asked whether they noticed any difference in the detection task between blocks, and if so, to explain it. Participants who correctly identified the manipulation were asked whether they became aware during the task or in hindsight.

2.5. EEG recording and pre-processing

Electroencephalography (EEG) was recorded from 64 locations on the scalp throughout the experiment with a sample rate of 1000 Hz using a Brain Products ActiChamp system. Horizontal electro-oculogram (HEOG) was recorded from the outer canthi of the eyes. Offline data analysis (Brain Vision Analyzer, Brain Products GmbH) included interpolation of bad channels, identified manually, on a participant-by-participant basis. A second order Butterworth zero-phase band-pass filter with low cut-off of .1 Hz and a high cut-off of 40 Hz, and a 50 Hz zero-phase notch filter was applied to each participant's

continuous data and data was re-referenced to the average of all 64 electrodes. Eye-blinks were corrected in a semi-automatic mode, using ocular correction independent component analysis (ICA). ERPs were epoched into 900 msec segments ranging from 100 msec pre-stimulus onset to 800 msec post-stimulus onset. A 100 msec pre-stimulus baseline correction was performed on each ERP by subtracting the mean voltage in that interval from every voltage point (1/msec) in the ERP. Artefact rejection was performed on all channels excluding segments with amplitudes exceeding $\pm 100 \mu\text{V}$. Participants with <50% trials from any one condition, after artefact rejection, were excluded. For EEG analysis pipeline, see <https://osf.io/tjp5u/>

3. Analysis pipeline

Behavioural and EEG analyses were performed on the same final sample of participants. The nine participants excluded following data preprocessing resulted in removal of both the behavioural and EEG data, and these participants were replaced. For all primary analyses, an alpha level of .05 was used. Where the assumption of sphericity is violated in repeated measures analyses of variance (ANOVA), Greenhouse–Geisser adjusted degrees of freedom and probability levels are reported. Partial eta squared is reported for ANOVA effects, and Cohen's d for t -tests. For all non-significant effects, Bayes Factor (BF) analysis was conducted and BF10 values of less than 1/3 are considered as support the null hypothesis compared to the theory (Dienes, 2014). Thus,

analysis referring to ‘No difference’ expects an effect of $BF_{10} < 1/3$.

3.1. Behavioural data

3.1.1. Detection task

Spacebar presses and response times (RT) in ms were recorded. We planned to replace participants with insufficient accuracy (i.e., target detection $<60\%$ and/or $>20\%$ keypresses to non-targets), but no participant fell below these thresholds. For each participant in the final sample, the percentage of targets correctly detected, the associated mean RT, and the percentage of erroneous keypresses in the RF, RV, AF, and AV conditions (collapsed across blocks) was computed. Participants had a maximum of 1200 msec to respond on each trial, or the response was counted as a miss.

Two by two repeated measures ANOVAs were used to examine variance in mean correct detection rates, RTs, and erroneous keypresses to non-targets as a function of temporal prediction (RF, RV, AF, AV conditions). Only significant main effects or interaction were intended to be followed up with planned paired t-tests. Based on Jones and Ward (2019) we predicted no main effect of Temporal position or Rhythm on target detection accuracy, but in line with evidence that temporal prediction boosts detection speed (e.g., Jones, Hsu, Granjon, & Waszak, 2017; Jones & Ward, 2019), we predicted detection RTs: RF $<$ RV $<$ AF $<$ AV.

3.1.2. Recognition task

Number key presses and associated RTs were recorded. Ratings 1–3 and 4–6 on the scale were collapsed into ‘no’ (new object) and ‘yes’ (old object) responses, respectively. The purpose of using the scale was to capture a broad range of yes and no responses to minimise individual differences in response bias (i.e., incorporating high confidence responses as well as guesses), but responses were not intended to be analysed according to confidence as this was not relevant to our aim. As no time limit was imposed on recognition judgements, liberal screening was applied based on recognition RTs, with individual trials removed only if they were excessively lengthy (>3 SD from the participants’ overall mean RT). This resulted in the removal of 2.68% of trials across all participants. We planned to replace participants who used a single response—‘yes’ or ‘no’—on $>90\%$ trials in one or more blocks, indicating a failure to understand or follow instructions (participants were informed that half of the objects were shown in the detection task and half were not, so they should respond yes/no roughly an equal number of times), however, no participants needed to be excluded based on this.

For each participant the mean proportion of hits (‘yes’ responses to old items), misses (‘no’ responses to old objects), false alarms (FA; ‘yes’ responses to new objects), and correct rejections (CR; ‘no’ responses to new objects) were recorded for the RF, RV, AF, and AV conditions, and used to calculate d' ($z[\text{hits}] - z[\text{FA}]$, in accordance with signal detection theory (Snodgrass & Corwin, 1988)) as a measure of sensitivity/recognition accuracy. Where hits or false alarms were at 100%, slight adjustment was applied ($(\text{proportion hits or FA} + .5)/[240 + 1]$). The following analyses were then performed:

Behavioural data manipulation checks:

1. One paired sample, one-tailed, t-test comparing d' in the RF condition to the AV condition (manipulation check explained previously). If d' is not greater in the RF than the AV condition, this will likely reflect an issue with the experimental protocol.
2. Four one sample t-tests to ascertain that mean overall recognition is above chance ($d' > 0$) in all conditions. This is a standard preliminary analysis as it would not be meaningful to compare conditions where memory is altogether absent. We fully expected that recognition would be above chance in all conditions, as has been shown numerous times in the literature using this paradigm. Chance levels of recognition would indicate a serious problem with the sample, and no further analysis would be conducted.
3. Variation in d' across blocks and the counterbalanced order of conditions was examined using a 8(block) \times 4(order) mixed ANOVA. The purpose was to provide insight into whether the effect of temporal structure could be mediated by these unwanted factors. Jones and Ward (2019) reported no variation in recognition across blocks or as a function of counterbalance order, so we did not expect any significant main effects or interaction. However, we intended to follow up any significant effects or interaction with t-tests.
4. The number of participants rated as aware versus unaware was recorded along with the respective recognition scores. We expected the number of aware participants to be low as is the case in previous studies manipulating temporal aspects of stimulus presentation, but if a roughly equal ratio was observed, we intended to compare recognition scores using a 2(rhythm) \times 2 (prediction) \times 2(awareness) mixed ANOVA with follow-up t-tests to examine any significant interaction.

3.2. ERP data

3.2.1. Data extraction

3.2.1.1. DETECTION TASK. Mean amplitudes for three ERP components were extracted for each condition: one early (N1), one mid (N2) and one late (Late positive deflection). For the N1 and N2 components the peak was defined as the greatest negativity, averaged across PO7/8 and all conditions between 100 and 220 msec and 220–350 msec respectively. Mean amplitudes were then extracted for each condition encompassing 30 msec either side of the N1 and N2 peak. For the late positive deflection, mean amplitudes were extracted for each condition between 400 and 800 msec. This time interval also encompasses the Dm effect (differences due to subsequent memory), an effect commonly observed in recognition memory research and related to strength of memory encoding (Paller & Wagner, 2002). Target items (animals) were not included in the analysis.

3.2.1.2. RECOGNITION TASK. Mean amplitudes for two ERP components were extracted for each condition for old and new items; the FN400 and LPC. For the FN400 a mean amplitude was extracted from electrode Fz between 300 and 500 msec and electrode P3 between 500 and 800 msec for the LPC. For both the FN400 and LPC, a difference in mean amplitudes was calculated for new compared to old items to produce an ‘old/new effect’ for subsequent statistical analysis.

3.3. Main hypotheses

Our alternative hypotheses were tested using a 2×2 repeated measures ANOVA to examine the effect of Rhythm (rhythmic, arrhythmic) and Temporal position (fixed, variable). Separate ANOVAs will be used for the DVs specified:

1. Mean d' scores
2. Mean amplitudes for ERP components at encoding
3. Mean amplitudes for old/new effects of ERP components at retrieval

The following main effects and interaction effects correspond to our predictions set out earlier:

1. A significant main effect of Rhythm such that the DV is greater in rhythmic compared to arrhythmic conditions (**Hypothesis 1**). Two planned paired samples t-test will show:
 - a. No difference between RF and RV.
 - b. No difference between RF and AF.
2. A significant main effect of Temporal position such that the DV is greater in fixed compared to variable conditions (**Hypothesis 2**). Two planned paired samples t-test will show:
 - a. No difference between RF and AF.
 - b. No difference between RV and AV.
3. A significant interaction between Rhythm and Temporal position (**Hypothesis 3**). Subsequently four planned t-tests will show:
 - a. Greater DV measure for RF compared to RV.
 - b. Greater DV measure for RV compared to AF.
 - c. Greater DV measure for AF compared to AV.
 - d. Greater DV measure for RF compared to AV.
4. A significant interaction between Rhythm and Temporal position (**Hypothesis 4**). Subsequent planned t-tests will show:
 - a. Greater DV measure for RF compared to RV.
 - b. Greater DV measure for RF compared to AF.
 - c. Greater DV measure for RV compared to AV.
 - d. Greater DV measure for AF compared to AV.
 - e. No difference between RV and AF.
5. No significant main effect or interactions (**Hypothesis 5**).

3.4. Exploratory encoding ERP analysis

There was a possibility that pre-stimulus mean voltage subtraction as a baseline correction technique may not have been suitable. Given that our paradigm included the quick presentation of stimuli and each block of stimuli formed one experimental manipulation, standard pre-stimulus subtraction techniques may have removed neural processes associated with the expectation of an event or indeed introduced artefactual differences (for a general discussion, see Urbach & Kutas, 2006). However, pre-stimulus mean voltage subtraction baseline corrections are still the standard in ERP research and is commonly used in investigation of neural entrainment. As such, in an exploratory analysis, we repeated our analysis for the ERP produced at encoding, as specified above, with the

only difference being in the pre-processing stage. Rather than implement a standard baseline correction, all data was high-pass filtered at .5 Hz aimed specifically at removing the need for baseline correction and suppressing DC voltage fluctuations as has been suggested (Widmann, Schröger, & Maess, 2015) and conducted in the past (e.g., Herrmann, Henry, Fromboluti, McAuley, & Obleser, 2015). Below we report and comment on any effects that differed in significance ($p < .05$) from the main analyses outlined above.

4. Results

For raw data, averaged data, and analysis results files, see <https://osf.io/tjp5u/>.

4.1. Behavioural results

4.1.1. Detection task

The percentage of targets correctly detected, the associated mean RT, and the percentage of erroneous keypresses in the RF, RV, AF, and AV conditions (collapsed across blocks) is given in Table 1. There was no main effect of Rhythm ($p = .387$, $BF_{10} = .23$), or Temporal position ($p = .966$, $BF_{10} = .15$) on the correct detection of targets, and no interaction ($p = .669$, $BF_{10} = .23$). There were also no effects on detection RTs (Rhythm: $p = .163$, $BF_{10} = .53$, Temporal position: $p = .082$, $BF_{10} = .45$, Rhythm \times Temporal position interaction: $p = .927$, $BF_{10} = .23$). However, there was a main effect of Temporal position on erroneous keypresses to nontargets, $F(1, 53) = 13.24$, $p < .001$, $\eta_p^2 = .20$ (AV > RF, $t(53) = 3.07$, $p = .003$, $d = .42$; RV > RF: $t(53) = 2.93$, $p = .005$, $d = .40$; no other significant differences, $p > .05$ [planned two-tailed paired t tests]), but no main effect of Rhythm ($p = .461$, $BF_{10} = .186$), and no Rhythm \times Temporal position interaction ($p = .527$, $BF_{10} = .26$).

4.1.2. Recognition task

Mean proportions of hits, misses, false alarms, and correct rejections in the RF, RV, AF, and AV conditions are given in Table 3, and d' in Fig. 4. The following manipulation checks are numbered to correspond to analyses outlined in the analysis pipeline: (1) Comparison of d' in the RF and AV conditions revealed no significant difference ($p = .714$, $BF_{10} = .11$). (2) The one sample t-tests confirmed that recognition was above chance ($d' > 0$) in all conditions: RF: $t(53) = 23.49$, $p < .001$, $d = 3.20$; RV: $t(53) = 21.81$, $p < .001$, $d = 2.98$; AF: $t(53) = 22.58$, $p < .001$, $d = 3.07$; AV: $t(53) = 23.30$, $p < .001$, $d = 3.17$. (3) The 8(Block) \times 4(Order) mixed ANOVA revealed a main effect of Block, $F(4.80, 239.44) = 9.62$, $p < .001$, $\eta_p^2 = .16$, no main effect of Order ($p = .729$, $BF_{10} = .21$), and no interaction ($p = .713$, $BF_{10} = .01$). Follow-up planned t tests comparing d' across blocks revealed several reliable differences (Table 2 and Fig. 3). (4) Four participants were rated as aware of the temporal manipulation during the study, and d' scores were similar to the 50 unaware participants (RF: aware $M = 2.55$, unaware $M = 2.95$; RV: aware $M = 2.51$, unaware $M = 2.94$; AF: aware $M = 2.36$, unaware $M = 3.01$; AV: aware $M = 2.61$, unaware $M = 2.99$). Given the low number of aware participants, no further analyses were conducted.

Table 1 – Performance in the detection task.

	RF M (SD)	RV M (SD)	AF M (SD)	AV M (SD)
Correct detection (%)	94.18 (9.63)	94.65 (8.52)	93.52 (8.82)	92.95 (10.52)
Erroneous keypresses (%)	.10 (.37)	.46 (.89)	.23 (.52)	.46 (.81)
RT (correct)	557 (88)	567 (83)	568 (101)	580 (94)

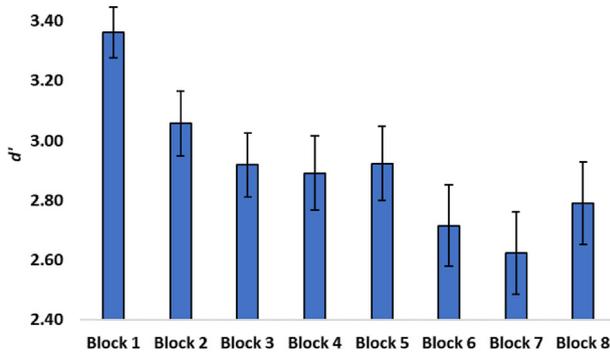


Fig. 3 – Recognition (d') in Blocks 1–8. Error bars indicate standard error of the mean (SEM).

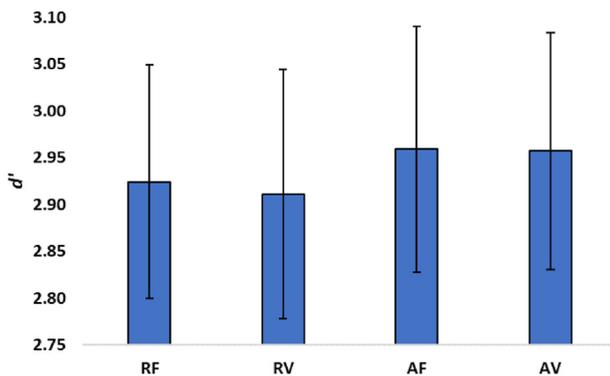


Fig. 4 – Recognition (d') in the RF, RV, AF, and AV conditions. Error bars indicate standard error of the mean (SEM).

Table 2 – Differences in d' across blocks.

Block	p	d
1 vs 2	.005	.40
1 vs 3	<.001	.65
1 vs 4	<.001	.63
1 vs 5	<.001	.51
1 vs 6	<.001	.68
1 vs 7	<.001	.77
1 vs 8	<.001	.57
2 vs 6	.002	.45
2 vs 7	<.001	.54
2 vs 8	.027	.31
3 vs 6	.042	.28
3 vs 7	.012	.36
4 vs 7	.008	.37
5 vs 6	.012	.36
5 vs 7	.002	.44

Note: all other comparisons ns, p 's > .05.

Our alternative hypotheses were tested using a 2(Rhythm) × 2(Temporal position) repeated measures ANOVA. There was no main effect of Rhythm ($p = .551$, $BF_{10} = .18$), no main effect of Temporal position ($p = .904$, $BF_{10} = .15$), and no interaction ($p = .915$, $BF_{10} = .21$).

Supplementary recognition analyses: Although not part of the pre-registration analysis pipeline, we examined the effects of Rhythm and Temporal position on recognition response times (RTs) using a 2 × 2 ANOVA (RTs can be found in Table 3). Similarly, to the main analysis, there were no main effects or interaction (all $p > .05$).

4.2. Exploratory recognition analysis

Given the null finding of our alternative hypotheses and that block had an effect on d' we explored further the effect of block by analysing reaction times for Hits as a function of Block. An 8 (Block) × 4(Order) repeated measures ANOVA on reaction times to Hits, showed a significant effect of Block, $F(3.82, 190.84) = 26.03$, $p < .001$, $\eta_p^2 = .08$ (Fig. 5). Follow-up Bonferroni corrected t tests comparing RT across blocks revealed several reliable differences (Table 4). There were no other main or interaction effects (all $p > .05$).

4.3. ERP results

4.3.1. Encoding ERPs

Analysis of encoding ERPs included the factors Rhythm (rhythmic, arrhythmic), and Temporal position (fixed, variable). ERPs for each condition were averaged across electrodes PO7 and PO8. The N1 peak, determined across all conditions was at 152 msec post stimulus onset and the analysis window averaged ERP amplitude in the 122–182 msec interval were analysed. The N2 peak was observed at 254 msec across all

Table 3 – Mean proportions of hits, misses, false alarms, and correct rejections in the recognition task, and response times (RT) broken down by recognition response.

	RF M (SD)	RV M (SD)	AF M (SD)	AV M (SD)
Hits	.89 (.11)	.89 (.11)	.89 (.11)	.89 (.12)
Misses	.11 (.11)	.11 (.11)	.11 (.11)	.11 (.12)
False alarms	.10 (.08)	.11 (.11)	.10 (.10)	.09 (.10)
Correct rejections	.90 (.09)	.89 (.11)	.90 (.09)	.91 (.10)
Overall RT	858 (569)	872 (684)	812 (497)	864 (556)
RT hits	660 (430)	668 (538)	625 (390)	641 (390)
RT misses	1295 (1022)	1415 (1187)	1253 (931)	1341 (1190)
RT false alarms	1593 (875)	1470 (880)	1426 (1129)	1460 (911)
RT correct rejections	966 (646)	969 (748)	907 (567)	987 (636)

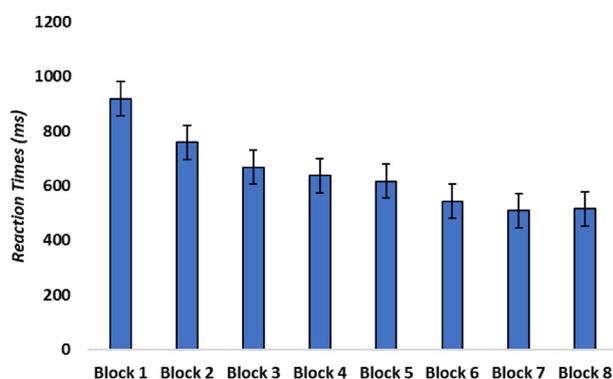


Fig. 5 – Reaction time (msec) for Hits in during recognition in Blocks 1–8. Error bars indicate standard error of the mean (SEM).

Table 4 – Differences in RT to hits across blocks.

Block	<i>p</i>	<i>d</i>
1 vs 2	.001	.35
1 vs 3	<.001	.54
1 vs 4	<.001	.61
1 vs 5	<.001	.66
1 vs 6	<.001	.82
1 vs 7	<.001	.89
1 vs 8	<.001	.88
2 vs 4	.045	.27
2 vs 5	.007	.31
2 vs 6	<.001	.47
2 vs 7	<.001	.54
2 vs 8	<.001	.53
3 vs 6	.033	.27
3 vs 7	.001	.35
3 vs 8	.002	.33
4 vs 7	.028	.28
4 vs 8	.045	.27

Note: All other comparisons ns, *p*'s > .05.

conditions over PO7/PO8 and the window analysed was 224–284 msec post stimulus onset. The Dm analysis time interval was pre-determined and set to 400–800 msec.

4.3.2. N1 component

There was a main effect of Rhythm, $F(1, 53) = 4.41$, $p = .041$, $\eta_p^2 = .08$, with rhythmic items ($M = 1.14$, $SE = .52$) showing more negative N1 amplitude compared to arrhythmic items ($M = 1.44$, $SE = .48$). There was also a main effect of Temporal position, $F(1, 53) = 22.00$, $p < .001$, $\eta_p^2 = .29$, with items with a fixed position showed more negative amplitude ($M = .97$, $SE = .52$) compared to variable position ($M = 1.62$, $SD = .50$). There was a significant Rhythm*Position interaction $F(1, 53) = 5.43$, $p = .024$, $\eta_p^2 = .09$.

Follow up *t*-tests showed a significant difference between RF versus RV, $t(53) = -4.90$, $p < .001$, $d = .67$, and RF versus AF, $t(53) = -2.88$, $p = .006$, $d = .39$, and RF vs AV, $t(53) = -4.85$, $p < .001$, $d = .66$. There was no difference between RV vs AF ($p = .089$, $BF_{10} = .60$), RV vs AV ($p = .959$, $BF_{10} = .49$), or AF and AV ($p = .052$, $BF_{10} = .92$).

4.3.3. N2 component

There was a main effect of Temporal position, $F(1, 53) = 6.63$, $p = .013$, $\eta_p^2 = .11$, with a more negative amplitude for items presented in a fixed ($M = 3.68$, $SE = .54$) compared to variable position ($M = 4.12$, $SE = .59$). There was no effect of Rhythmic presentation ($p = .994$, $BF_{10} = .07$), or Temporal position*Rhythm interaction ($p = .315$, $BF_{10} = .30$).

4.3.4. Dm time interval

There was a main effect of Temporal position, $F(1, 53) = 21.91$, $p < .001$, $\eta_p^2 = .29$, with a more negative amplitude for items presented in a fixed ($M = -.05$, $SE = .51$) compared to variable position ($M = .84$, $SE = .55$). There was no effect of Rhythmic presentation ($p = .139$, $BF_{10} = .38$), or Temporal position*Rhythm interaction ($p = .235$, $BF_{10} = .46$).

Taken together the N1 showed an interaction between Rhythm and Temporal position driven by a greater amplitude for RF compared to the other three conditions (see Fig. 6). The N2 and Dm interval showed a difference between items if they were presented in a fixed compared to a variable position, whilst there was no effect of rhythm at these two components.

4.3.5. Exploratory analysis using high-pass filter instead of baseline correction

As outlined above, we repeated the encoding ERP analysis for each component and instead of using a baseline correction, we applied a .5 Hz high pass filter (eight order, zero phase Butterworth) applied to continuous (non-segmented) data.

4.3.6. N1 exploratory

There was a main effect of Rhythm, $F(1, 53) = 6.01$, $p = .018$, $\eta_p^2 = .10$, with rhythmic items ($M = .154$, $SE = .38$) showing more negative N1 amplitude compared to arrhythmic items ($M = .39$, $SE = .88$). There was a borderline main effect of Temporal position, $F(1, 53) = 4.03$, $p = .050$, $\eta_p^2 = .07$, with items with a fixed position showed more negative amplitude ($M = .18$, $SE = .39$) compared to variable position ($M = .36$, $SD = .36$). There was no significant Rhythm*Temporal position interaction ($p = .256$, $BF_{10} = .40$).

4.3.7. N2 exploratory

There was no main effect of Temporal position ($p = .424$, $BF_{10} = .19$) or Rhythmic presentation ($p = .427$, $BF_{10} = .20$), and no Temporal position*Rhythm interaction ($p = .979$, $BF_{10} = .20$).

4.3.8. Dm exploratory

There was no main effect of Temporal position ($p = .346$, $BF_{10} = .674$) or Rhythmic presentation ($p = .065$, $BF_{10} = .25$), and no Temporal position*Rhythm interaction ($p = .458$, $BF_{10} = .25$).

The exploratory analysis showed similar main effects of Rhythm and Temporal position at the N1 component. However, there was no interaction effect as observed in the main analysis above. Moreover, there was no Temporal position effect at the N2 or Dm in the exploratory high-pass filter analysis, as compared to the baseline corrected results above.

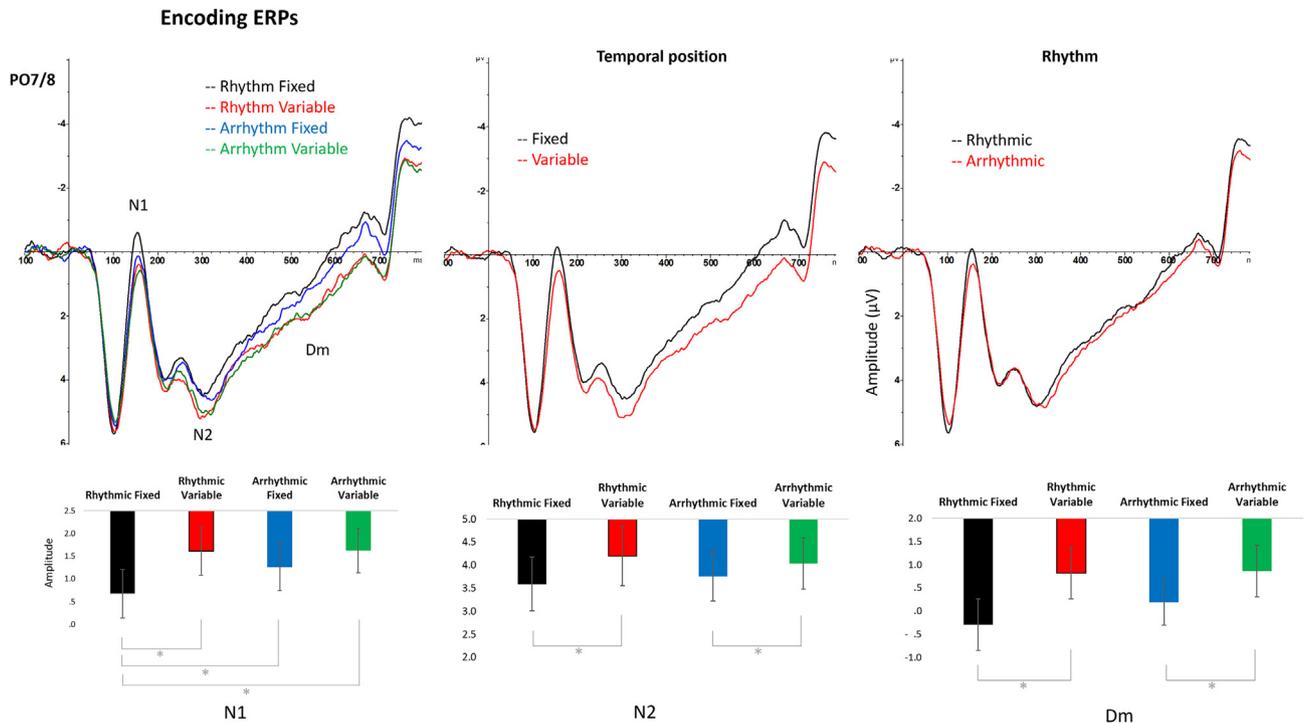


Fig. 6 – Top row Left – grand average ERPs for each of the four condition separately at encoding. Time 0 msec is the onset of an item. Top row Middle – grand average ERPs showing the main effects of Temporal position which includes the average of Rhythm Fixed and Arrhythmic Fixed (black) and Rhythm Variable and Arrhythmic Variable (red). Rhythm (Top row Right) shows the average of Rhythm Fixed and Rhythm Variable (black) and Arrhythmic Fixed and Arrhythmic Variable (red). All ERPs show the electrodes PO7/8 pooled together. Bottom row – mean ERP amplitudes for each of the four conditions and each analysed component.

4.3.9. Exploratory analysis summary

At the suggestion of a reviewer at the Stage 1 Registered Report review, we included this exploratory analysis in case any baseline correction, as typically applied to ERP analysis, removed critical variability related to the rhythmic presentation of stimuli. This analysis was therefore more liberal in its approach aimed at finding effects perhaps hidden in the primary analysis. Although the results of our exploratory analysis differ from our main analysis, no new differences are unearthed by it and as such we don't consider it further here.

4.4. Recognition ERPs

4.4.1. FN400 old/new effect

A difference amplitude in the 300–500 msec interval at Fz between hits (old) and correct rejections (new) items were included in the analysis with the factors Rhythm (rhythmic, arrhythmic) and Temporal position (fixed, variable).

There were no main effects of Rhythm ($p = .913$, $BF_{10} = .15$) nor Temporal position ($p = .587$, $BF_{10} = .17$), however, there was a Rhythm*Temporal position interaction, $F(1, 53) = 7.35$, $p = .009$, $\eta_p^2 = .12$. Planned follow up t-tests showed a significant difference between AF and AV conditions ($t(53) = -2.38$, $p = .021$, $d = .32$) indicating a larger FN400 old new effect for AV condition ($M = 1.27$, $SE = .21$) compared to AF condition ($M = .60$, $SE = .24$) (see Figs. 7 and 8). There was no significant difference between RF versus RV ($p = .147$, $BF_{10} = .41$), RF vs AF ($p = .089$, $BF_{10} = .60$) and RV vs AV ($p = .058$, $BF_{10} = .84$).

4.4.2. LPC old/new effect

There were no main effects of Rhythm ($p = .207$, $BF_{10} = .31$), Temporal position ($p = .483$, $BF_{10} = .19$), or Rhythm*Temporal position interaction ($p = .067$, $BF_{10} = .87$).

4.4.3. Supplementary FN400 old new effect results

The analysis above, specified in the pre-registration, contrasts the FN400 old/new effect across the conditions. However, it does not include whether an FN400 old/new effect is present or absent. To supplement the above analysis, we have also included tests to confirm the presence or absence of the old/new effect. This analysis was not specified in the pre-registration and does not change any interpretation of the above results, it simply adds information about the effects being compared. Separate t-tests were conducted for each condition comparing old vs new items in the FN400 interval. No correction for multiple comparisons has been made as this analysis is conformity in nature and was omitted from the pre-registration in error. There was a significant difference between old (hits) and new items (correct rejections) in all four conditions: RF old/new effect, $t(53) = 5.68$, $p < .001$, $d = .77$, (Fig. 8A) (old – $M = -1.52$, $SE = .45$, and new items – $M = -2.70$, $SE = .45$); RV old/new effect, $t(53) = 3.66$, $p = .001$, $d = .50$, (Fig. 8B) (old – $M = -1.96$, $SE = .46$ and new items – $M = -2.70$, $SE = .43$); AF old/new effect: $t(53) = 2.49$, $p = .016$, $d = .34$, (Fig. 8C) (old – $M = -2.02$, $SE = .44$ and new items – $M = -2.62$, $SE = .47$); and AV old/new effect, $t(53) = 6.04$, $p < .001$, $d = .82$, (Fig. 7D) (old – $M = -1.83$, $SE = .45$, and new items – $M = -3.10$, $SE = .45$).

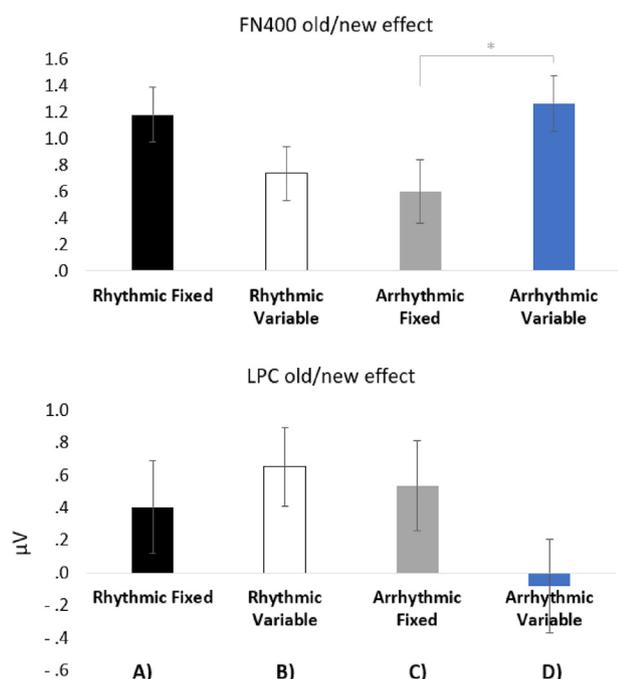


Fig. 7 – The bar charts show the size of each old/new effect at the FN400 (top) and LPC (bottom) for each of A) Rhythmic Fixed, B) Rhythmic Variable, C) Arrhythmic Fixed and D) Arrhythmic Variable conditions. There was a significant difference between the FN400 old/new effect between Arrhythmic Fixed (C) and Arrhythmic Variable (D), with a larger difference between old and new items in the Arrhythmic Variable condition (see also C and D – Fig. 8). The LPC old/new effects did not differ between conditions. Note. Error bars are standard error of the mean and the y-axis is amplitude, measured in micro-volts (μV).

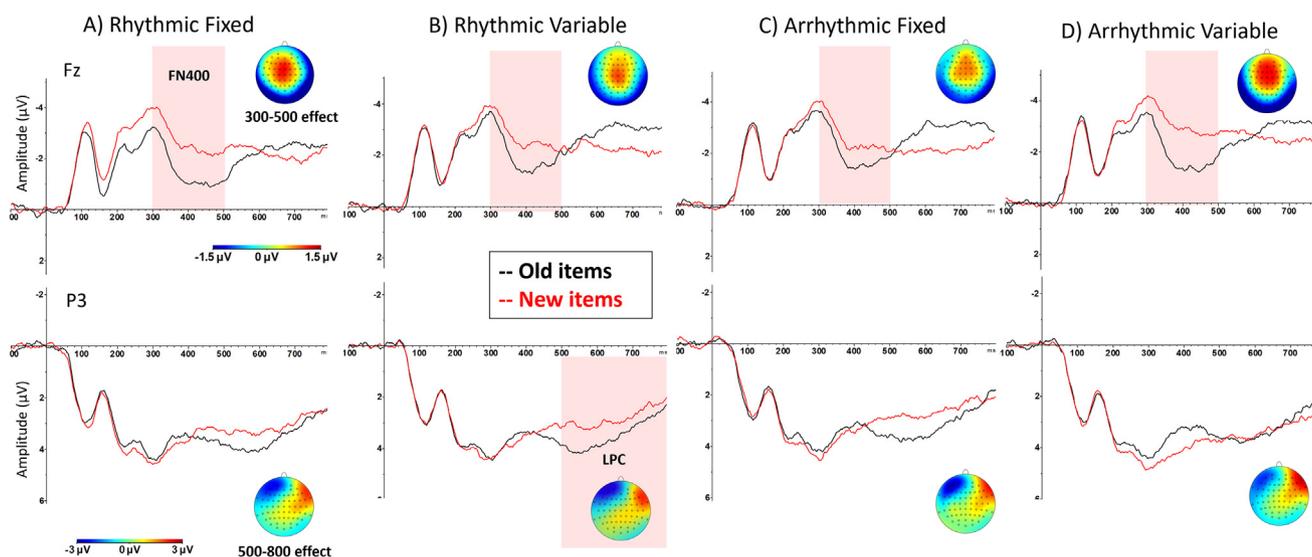


Fig. 8 – Recognition task ERPs for each of the four conditions. Waveforms show grand averaged ERPs for old items (black) and new items (red) with 0 msec being item onset. ERPs include accurate responses only, that is; hits (black) and correct rejections (red). There was a significant FN400 old/new effect in all four conditions between 300 and 500 msec at Fz (top row). An LPC old/new effect, analysed at electrode P3 (bottom row) in the 500–800 msec interval, was only present in the Rhythmic variable condition (B). Topographical maps show the difference between old-new waveforms for the 300–500 msec interval (top row) and 500–800 msec interval (bottom row).

4.4.4. Supplementary LPC old/new effect analyses

A separate t-test was conducted for each condition comparing old (hits) and new items (correct rejections) in the 500–800 msec LPC interval to confirm the presence or absence of the LPC old/new effect. This analysis showed a presence of a LPC old/new effect only in the RV condition, $t(53) = 2.71$, $p = .009$, $d = .37$ (Fig. 8B) (old – $M = 3.46$, $SE = .42$ and new items – $M = 2.81$, $SE = .35$). There was no significant LPC old/new effect in the other three conditions: RF ($p = .159$, $BF_{10} = .39$) (Fig. 8A), AF ($p = .059$, $BF_{10} = .83$) (Fig. 8C), and AV condition ($p = .783$, $BF_{10} = .15$) (Fig. 8D).

5. Discussion

Prior research has shown that temporal prediction aids memory formation. Both isochronous rhythms and aperiodic temporal regularities have been manipulated in past studies, but here we set out to examine the independent contribution of these factors. We systematically manipulated rhythm (rhythmic vs arrhythmic stimulus onset timings) and temporal position (fixed vs variable position of real objects in the stimulus stream) during encoding to determine their independent effects on subsequent recognition of objects and neural correlates. Our four alternative hypotheses predicted different outcomes based on whether memory is driven purely by entrainment to rhythm, purely by non-rhythmic temporal prediction, or a unique combination of the two. However, the present behavioural data showed no effect of either factor on recognition memory. This is in contrast to our own previous findings that show rhythmic presentation of items at encoding leads to greater recognition than arrhythmic presentation (Jones, Ward, Csiszer, & Szymczak,

2022; Jones & Ward, 2019), and is also inconsistent with other studies that have reported beneficial effects of temporal predictability on memory (e.g., Hickey et al., 2020; Johndro et al., 2019; Thavabalasingam et al., 2016). Although we did not observe behavioural effects on memory, analysis of the neural data shows effects of both temporal position and rhythm in the encoding task. The N1 component was larger in amplitude for the rhythmic fixed condition, compared to the other three conditions. Later stages of item processing, the N2 and Dm components, showed effects of temporal position only. We discuss the behavioural and ERP results in detail below.

Based on our prior observations (Jones et al., 2022; Jones & Ward, 2019), and those of others (e.g., Hickey et al., 2020; Johndro et al., 2019; Thavabalasingam et al., 2016), we assumed in all our hypotheses that recognition would be greatest overall when temporal predictability was at its highest, i.e., in the rhythmic fixed (RF) condition. Further, we assumed that recognition would be weakest when stimuli were presented in the least temporally predictable manner – that is, in the arrhythmic variable (AV) condition. This is because in the RF condition participants were able to anticipate both the onset of stimuli and the temporal position of real objects in the encoding phase, while in the AV condition they were not able to predict stimulus onset nor the temporal position of real objects. We specified observing a significant difference between these conditions as a manipulation check. This was based on the available evidence when at the time of writing the Stage 1 Registered Report (Hickey et al., 2020; Johndro et al., 2019; Jones et al., 2022; Jones & Ward, 2019; Thavabalasingam et al., 2016). However, the current landscape is now much more mixed in relation to the effect of temporal prediction on memory. The beneficial effect of temporal predictability on recognition appears to be more elusive than we previously thought. For example, Kulkarni and Hannula (2021) reported no benefit to recognition memory for items (objects and scenes) presented with a predictable versus a random sequence of onset timings during encoding. Their methods were closely modelled on Thavabalasingam et al. (2016) (outlined in the Introduction) but also included new test items that were perceptually similar to studied items in order to examine whether the benefit of temporal prediction extends to item-specific detail. Temporal prediction did not improve recognition in any of their three experiments, and the authors concluded that any effect of temporal expectation on memory is subtle and likely sensitive to small changes in experimental parameters. Similarly, Kunert and Jongman (2017) presented participants with words either in synchrony or out of synchrony with an auditory rhythm. They found faster response times to in-synchrony targets, however, there was strong evidence for the null hypothesis – i.e., no effect of rhythm on later recognition memory. Further, in contrast to our initial published studies showing reliable effects of rhythmic encoding on recognition (Jones et al., 2022; Jones & Ward, 2019), new unpublished data from our lab struggled to replicate these findings and has shown no effect of rhythm on recognition across several experiments. These include lab-based studies varying local effects of rhythm by presenting stimuli in an out of synchrony, as well as a near direct replication of our previous Jones and Ward (2019) study across age groups. Similarly, we have attempted to replicate

the effect of rhythm on recognition memory using an online study but found no effect.

Based on the emerging lack of consensus surrounding the effect of temporal prediction on memory, we do not believe that the present null difference in recognition between the RF and AV conditions reflects an issue with the experimental protocol as was initially stated in our Stage 1 analysis pipeline. Recognition levels were above chance in each of the four conditions (RF, RV, AF, AV), confirming that participants engaged in the task and were able to encode to-be-remembered items. It is also worth noting that the same stimuli and timings used in Jones and Ward (2019) were employed here. However, if any effect of temporal prediction is small, it is possible that it may have been washed out by other minor differences between our current task and the previous one. One difference between this and our earlier study is the increased number of blocks – 8 in the present study versus 6 in Jones and Ward (2019). Here recognition was significantly greater in the first block than all other blocks, and there were several other significant comparisons between blocks, while in our earlier study there was no variation across blocks. In the present study recognition got progressively worse over time (i.e., across blocks), but there was no interaction with the counterbalanced order of conditions. This may suggest that increased participant fatigue and waning of sustained attention contributed to obscuring any effect of temporal predictability. Given that reaction times and d' decreased as experimental blocks increased, suggesting a speed-accuracy trade off, a general lack of attentional disengagement may be a better explanation than fatigue. These findings, are consistent with an elusive effect lacking robustness and is further supported by the ambiguous nature of our null finding – the Bayes Factor analysis provides neither support for the null or alternative hypotheses.

Given that we initially defined a difference in recognition accuracy between the RF and AV conditions as a manipulation check, it is important that we consider the possibility that the lack of a difference is due to issues with the experimental protocol. Specifically, we address the possibility that there was an issue with the stimuli presentation and timing acuity during encoding. We find this an unlikely explanation for two reasons. First, we carefully checked and validated the presentation timing in our lab setup including using a photo diode sensor to examine any variability in the stimulus presentation timing. Second, the ERP results during the encoding show differences based on our temporal predictability manipulations, which we discuss in detail below. Such differences strongly suggest that the present temporal predictability manipulations had an effect on participant processing during encoding and serve as a useful validation of the accuracy of our timing presentation. Given the null effect of our manipulations on behavioural recognition, we turn our attention to the changes in ERP activity.

Analysis of the N1 component showed an interaction between temporal position and rhythm with larger amplitude for the rhythmic fixed condition compared to all other conditions. This suggest that early perceptual processing is affected by both forms of prediction – position and rhythm. This most closely corresponds to our pre-determined Hypotheses 3 and 4 (Fig. 1) whereby the combined effects of rhythm and position

are involved in modulating stimulus processing. These findings are in line with the numerous studies showing that entraining a rhythm affects early sensory processes (e.g., Bouwer & Honing, 2015; Escoffier et al., 2015; Fitzroy & Sanders, 2015) and increasing the neural gain (Auksztulewicz, Myers, Schnupp, & Nobre, 2019). Moreover, these findings suggest that early sensory processing are influenced specifically by these two forms of expectation when combined but not when isolated and operating individually (see also Auksztulewicz et al., 2018; Doherty, Rao, Mesulam, & Nobre, 2005). It is also possible that the fixed temporal position of the object also entrained a rhythm. Unlike in any other condition this would mean a rhythm was present for all stimuli and then a slower additional rhythm for the objects presented rhythmically every 4800 msec (once every fourth item). This combined effect of two rhythms may also explain enhanced perceptual processing indicated by a greater N1 amplitude.

The mid (N2) and late (Dm) stages of processing showed an effect of temporal position only. That is, the later stages of processing were best explained by our pre-determined Hypothesis 2 (see Fig. 1) suggesting neural processing at this stage is only affected by temporal position but not rhythm. There is evidence suggesting that these post-perceptual processes such as the N2 and late positivity are particularly sensitive to the effect of temporal prediction (e.g., Griffin et al., 2002; Miniussi et al., 1999; Rolke et al., 2016, see Correa et al., 2006 for a review).

Interestingly, the overall pattern of results is consistent with a study by Hsu, Hämäläinen, and Waszak (2013) who found a dissociation between early and late stages of processing. They found that temporal expectation affected early sensory components whilst spectral expectation (the prediction of *what* will appear) affected later stages of processing. During encoding in this study, we presented a stimulus on each trial but whether that stimulus was a checkerboard or an image to be remembered was manipulated by our temporal position conditions; in fixed conditions participants could predict what would appear, in variable ones they could not. In light of this, our findings, for the latter ERPs (N2 and Dm) may be described as indicative of spectral processing – reflecting the prediction of ‘what’ will appear. Although the present study shows measurable effects of prediction during encoding on the brain, it is important to note that these did not translate to our behavioural measure of cognition – recognition memory. Obviously, in addition to the many forms of temporal prediction that can affect encoding, long term memory is a complicated process subserved by many distinct lower level perceptual and cognitive systems. Recently, van de Ven, Kleuters, and Stuiver (2023) presented pictures synchronously or asynchronously with audio or visual backgrounds. They found no effect of multisensory synchrony on recognition memory. However, they did find that multisensory synchrony affected temporal associative memory (see also Clouter et al., 2017 for effects of synchrony on associative memory). Thus, it may be that different forms of memory or methods of memory measurement are more or less sensitive to the effects of manipulations of temporal expectation.

At recognition the ERPs provide no further insight into the effects of temporal position on memory. Whilst we confirm the presence of the FN400 – a clear difference between old and

new items at recognition, the only effect of temporal position is not one predicted by any of our hypotheses and contradicts our previous null findings of temporal position on the FN400 (Jones et al., 2022; Jones & Ward, 2019). Specifically, the old/new effect of the FN400 differed for stimuli encoded during fixed compared to variable temporal positions for arrhythmic presentation only (Fig. 6). Given that this finding doesn't conform to any of our hypotheses nor replicate our previous work, we offer no speculative account and merely suggest that further replication is needed.

Overall, our results contribute to the current landscape of mixed findings in relation to how time and temporal expectations influence memory. Whilst we report notable effects on early and mid-range processing as indicated by our ERP results, behavioural recognition appears to be unaffected. Looking to the future, a systematic evaluation of what manipulations in temporal expectation affect different forms of memory is needed, however, we implore caution as any effect seems to lack robustness and may not be meaningful in day-to-day cognition.

CRediT author statement

Alexander Jones: Conceptualization, Methodology, Software, Formal analysis, Resources, Data Curation, Writing – Original Draft, Visualization, Supervision, Project administration, Funding acquisition. **Emma Ward:** Conceptualization, Methodology, Software, Formal analysis, Resources, Data Curation, Writing – Original Draft, Visualization, Supervision, Project administration, Funding acquisition. **Wayne Anderson:** Software, Formal analysis, Investigation, Data Curation, Writing – Review & Editing, Visualization, Project administration. **Jonathan Silas:** Conceptualization, Methodology, Software, Formal analysis, Resources, Data Curation, Writing – Original Draft, Visualization, Supervision, Project administration, Funding acquisition.

Open practices

The study in this article earned Open Data and Open Materials badge for transparent practices. The data and materials used in this study are available at: <https://osf.io/tjp5u/>.

Acknowledgements

This work is supported by a grant from the Bial Foundation (No. 111/18) awarded to Emma V. Ward, Alexander Jones and Jon Silas.

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