INTRODUCTION

Sequence learning has been implicated in the acquisition and use of motor skills (Ashe, Lungu, Basford, & Lu, 2006; Doyon et al., 2009) and higher order operations such as language and social skills (Hamrick, Lum, & Ullman, 2018; Van Overwalle, 2009). To date, only a handful of studies have used EEG to study sequence learning. As a consequence, little is known about the time course of the neurological activity associated with this type of learning. In this study, ERPs were used to examine the time course of neurological events associated with implicit sequence learning on the serial reaction time (SRT) task.

1.1 The SRT task

The SRT task was developed by Nissen and Bullemer (1987) and has been widely used to study the implicit learning of a visuospatial sequence in clinical and nonclinical populations (e.g., Clark & Lum, 2017; Janacsek, Fiser, & Nemeth, 2012; Robertson, 2007). In the standard version of the task, a visual stimulus repeatedly appears in one of four horizontal locations on a computer display. The participant’s task is to press one of four horizontally arranged buttons on a response panel that matches the location of the visual stimulus. Once a response is made, the stimulus appears in another location, and the participant is prompted to respond, and so on. In the “standard” Nissen and Bullemer (1987) version of the task, stimulus presentations are grouped into blocks comprising anywhere from around 50 (Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006) to over 100 trials (Gabay, Schiff, & Vakil, 2012). Unbeknownst to participants, on some blocks, the order in which the visual stimulus appears in the four locations follows a predetermined sequence. These blocks are hereafter referred to as
sequence blocks. After participants have completed multiple sequence blocks, a block of trials is then presented in which the stimulus randomly appears in one of the four positions. That is, the stimulus no longer follows the sequence. These are hereafter referred to as random blocks, but in the SRT literature they are sometimes referred to as control blocks.

In nonclinical groups (Thomas & Nelson, 2001; Thomas et al., 2004), reaction times (RTs) become faster as participants are exposed to the sequence blocks and then slow down when a random block is presented at the end of the task. This slowdown in RT indicates that knowledge about the sequence has been obtained. If it were the case that RT on the sequence blocks were only influenced by perceptual motor skills and not sequence knowledge, one would expect manual responses to become even faster or reach asymptote once the final random block is presented. Importantly, changes in RT across the SRT task can occur without participants being aware that a sequence was present (e.g., Bo, Jennett, & Seidler, 2011). Under these conditions, sequence learning is considered to be implicit.

1.2 | ERP studies of the SRT task

A number of studies have used ERPs to examine sequence learning on the SRT task (Eimer, Goschke, Schlaghecken, & Stürmer, 1996; Ferdinand, Mecklinger, & Kray, 2008; Ferdinand, Rüger, Frencs, & Mecklinger, 2010; Ferdinand, Weiten, Mecklinger, & Kray, 2010; Kopp & Wolff, 2000; Miyawaki, Sato, Yasuda, Kumano, & Kuboki, 2005; Rüsseler, Hennighausen, Münte, & Rösler, 2003; Rüsseler, Hennighausen, & Rösler, 2001; Rüsseler, Kuhlicke, & Münte, 2003; Rüsseler & Rösler, 2000; Schlaghecken, Stürmer, & Eimer, 2000). It should be noted that, in this literature, none of the studies have used the standard version of the SRT task described by Nissen and Bullemer (1987); i.e., trials presented in blocks comprising sequence stimulus presentations followed by a block comprising random stimulus presentations). Thus, potential ERP components associated with the more widely used Nissen and Bullemer (1987) version of the task have yet to be investigated.

In past ERP studies of sequence learning, the SRT task has been presented as an oddball paradigm designed to elicit N2 and P3 components (Näätänen, Pakarinen, Rinne, & Takegata, 2004). In oddball versions of the SRT task, the highly frequent standard trials comprised stimulus presentation that followed the sequence. The infrequent deviant trials were created by replacing a trial in which a stimulus presentation did not follow the sequence (e.g., Rüsseler, Hennighausen et al., 2003). In this literature, deviant trials have been found to elicit larger N2 and P3 components compared to standard trials. Thus, it seems that both components are sensitive to sequence learning on the oddball version of the SRT task. The N2 component appears to be elicited when sequence learning is implicit or explicit (Ferdinand et al., 2008; Ferdinand, Rüger et al., 2010; Schlaghecken et al., 2000). However, there is evidence to suggest that the P3 component is only observed when sequence learning is explicit (Ferdinand et al., 2008; Rüsseler et al., 2001; i.e., when participants become aware of the sequence or are informed of its existence prior to commencing the task).

1.3 | P1 and N1 ERP components and sequence learning on the SRT task

In the current study, we examined whether the visual P1 and N1 components might also be sensitive to sequence learning on the Nissen and Bullemer (1987) version of the SRT task. The P1 and N1 components appear as early as 80 and 140 ms poststimulus onset, respectively, and amplitudes are generally highest at occipital-parietal scalp recording sites (Hillyard & Anllo-Vento, 1998; Luck & Kappenman, 2011). The amplitude of these two components is modulated by attention. Specifically, allocating attention to a visual stimulus will increase the amplitude of the P1 and N1 components (Mangun, Hopfinger, Kussmaul, Fletcher, & Heinze, 1997; Vogel & Luck, 2000). Studying the P1 and N1 components in relation to the SRT task may provide new insights into the role of attention in implicit sequence learning. Indeed, the extent to which attentional processes are necessary for implicit learning have been an area of ongoing debate (Curran & Keele, 1993; Jiménez & Méndez, 1999; Staels & Van den Broeck, 2017).

The P1 and N1 components most likely capture different attentional processes (Coulle, 1998; Kotchoubey, 2006; Luck & Kappenman, 2012; Natale, Marzi, Girelli, Pavone, & Pollmann, 2006). Supporting this position is research showing dissociations between these two components. For example, a decrease in the amplitude of the P1 component, but not N1, has been observed when a visual stimulus unexpectedly appears in one spatial location that is not being attended (e.g., Luck et al., 1994). The N1 component can be independently modulated by varying the demands associated with evaluating a visual stimulus (Mangun & Hillyard, 1991). For example, evaluating whether a visual stimulus is of a certain color can lead to an N1 component that is larger in amplitude compared to evaluating whether a visual stimulus is present in a visual field (Vogel & Luck, 2000). These findings have led to the suggestions that the P1 component is modulated by attentional processes related to visuospatial processing and the N1 component by evaluation of a visual target (Vogel & Luck, 2000; Warbrick, Arrubla, Boers, Neuner, & Shah, 2014).

Two proposals from the SRT task literature suggest that sequence learning may modulate visuospatial attention and, as a consequence, the P1 component. According to one view, as participants acquire information about the sequence, they can anticipate forthcoming stimulus locations and shift
spatial attention to its expected location (Marcus, Karatekin, & Markiewicz, 2006; Nissen & Bullemer, 1987; Stadler, 1989). It has been repeatedly demonstrated (for a review, see Luck & Kappenman, 2012) that P1 amplitude increases when attention has been directed to a location where a visual stimulus will appear. Conversely, a decrease in P1 amplitude is observed when a visual stimulus appears in a noncued spatial location. Based on this literature, as participants complete more sequence blocks on the SRT task, P1 amplitude may increase as attention is already directed at forthcoming stimulus locations. However, on the random block, P1 amplitude should decrease. This is because sequence knowledge can no longer be used to cue participants to the location where the visual stimulus will appear.

A second view predicts P1 amplitude might decrease over sequence blocks on the SRT task. In a fMRI study of SRT task performance, Thomas et al. (2004) found parietal cortex activation was lower for sequence blocks compared to random blocks in adults. There is considerable evidence indicating that the parietal cortex plays a key role in visual-attentional processes (Corbetta, Shulman, Miezin, & Petersen, 1995). In light of this literature, Thomas et al. suggested that sequence learning might lead to a decrease in levels of visual attention needed to provide a manual response on the SRT task. This may occur because, once the knowledge of the sequence has been acquired, manual responses to the visual stimulus become automatized and less contingent on the need to attend to the visual stimulus. Based on these findings, one would expect sequence learning on the SRT task to lead to a decrease in P1 amplitude. There may also be a decrease in N1 amplitude since this component captures visual attentional processes. In responding to trials on the random block, attention would be needed to respond to the visual stimulus. As a consequence, P1 and N1 amplitude should increase on this part of the task.

1.4 Current study

The aim of the current study was to examine whether changes in P1 and N1 ERP components would be sensitive to implicit learning of a visuospatial sequence on the SRT task. In this study, healthy adults completed a version of the SRT task described by Nissen and Bullemer (1987). Specifically, blocks of trials were presented to participants comprising sequence or random stimulus presentations. Participants were not informed of the sequence prior to testing. Given this, the study examined ERPs related to implicit sequence learning. The hypothesis put forward in this study was that implicit sequence learning on the SRT task would modulate the P1 or both P1 and N1 components. An exploratory arm of the study examined whether a version of the Nissen and Bullemer SRT task would elicit N2 and/or P3 ERP components. As noted earlier, previous research using oddball versions of the SRT task report that N2 and P3 components are sensitive to sequence learning effects (e.g., Eimer et al., 1996; Ferdinand, Rünger et al., 2010; Rüsseler et al., 2001; Schlaghecken et al., 2000). However, to our knowledge whether the Nissen and Bullemer version of the SRT task also elicits these components has yet to be investigated.

2 METHOD

2.1 Participants

The final sample comprised 35 healthy adults (25 female) aged between 18 and 34 years (M = 22.7, SD = 3.4). The participants did not have visual or hearing impairments, psychiatric illnesses, or neuromotor diseases as indicated by a prescreening questionnaire. All participants had completed a minimum of secondary education. Participants provided written consent before taking part in the study and received a $30 voucher.

Prior to completing the SRT task, participants completed tasks that measured handedness and general cognitive functioning. Handedness was quantified using the Edinburgh Handedness Inventory (Oldfield, 1971). On this instrument, handedness is quantified using a laterality quotient that ranges from −1 to 1. Positive values indicate greater tendency to be right-handed and negative values, left-handed. All participants in this sample had laterality quotients greater than zero (M = 0.88, SD = 0.20). General nonverbal functioning was assessed using the matrices subtest from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). Performance on the matrices subtest is quantified as a T score, which is standardized to a mean of 50 and standard deviation of 10. The mean T score for the sample was 61.8 (SD = 5.7).

2.2 Materials

2.2.1 SRT task

The SRT task used in this study was based on the version described by Nissen and Bullemer (1987). Participants were seated in front of a computer display and presented with a four-button response panel. The task consisted of one practice block and six test blocks, with 60 trials in each block. A single trial consisted of a visual stimulus appearing in one of four horizontal locations on the computer display. Each location was vertically centered on the computer display. Each trial commenced with a blank screen (colored gray) for 500 ms. A visual stimulus then appeared in one of the four locations for 650 ms. Once the stimulus appeared, participants’ task was to press one of four buttons on a response box that matched the location of the visual stimulus. All participants used their right hand to make a response. Specifically, the first digit (or index finger) was used to operate the left-most response button, the second digit was used to operate the adjacent button, and so on. The stimulus remained on the screen for 650 ms.
irrespective of whether a response was made. If a response was not made during this time, the trial was marked as incorrect and the next trial commenced. No feedback was provided to participants as they completed the task. A schematic overview of the SRT task and stimuli is presented in Figure 1.

On the practice block, the visual stimulus appeared in each of the four locations an equal number of times, but in a pseudorandom order. The only constraint was that the stimulus could not appear in the same location on two consecutive trials. The purpose of the practice block was to familiarize participants with making a manual response following stimulus onset. Data from the practice block were not used in the analyses.

On the first five test blocks, unbeknownst to participants, the location that the stimulus appeared in the four spatial locations followed a predetermined sequence. These five test blocks are hereafter referred to as S1, S2, S3, S4, and S5. Between each block there was a 3-s rest period. Labeling the left-most location that the stimulus could appear as 1 and the right-most position as 4, the sequence used was 3–4–1–2–4–1–3–4–2–1. This sequence can be considered a first-order conditional sequence. In this type of sequence, the position that a stimulus appears on a single trial is predicted, to varying degrees of probability, by the position of the stimulus in the preceding trial. For example, if the visual stimulus appears in Position 2, there is a 50% probability the next stimulus will appear in Position 4 or Position 1. There is 0% probability the visual stimulus will appear in Position 3. On the final test block, a visual stimulus appeared in pseudorandom positions. This final test block is hereafter referred to as R6. The constraints for this block were that a visual stimulus (a) appeared in each location the same number of times as for S1–S5, and (b) could not appear in the same location on two consecutive trials. Additionally, none of the first-order transitions in the random sequence matched those found in the repeating sequence.

Unlike most versions of the SRT task, boxes or borders were not used to mark the four horizontal locations where the visual stimulus could appear. This modification was made to avoid the boxes acting as an external cue to indicate where the visual stimulus might appear and to reduce awareness of the sequence. Thus, the screen was blank between stimulus presentations. The only potential cue to indicate the location of the visual stimulus on any given trial was its location in the previous trial. Also, unlike the standard SRT task, a different visual stimulus appeared on each trial. A total of 60 different visual stimuli were created for this experiment. The stimuli comprised 60 different shapes (e.g., square, triangle, odd-shaped polygons) of different colors (green, blue, magenta, pink, purple, yellow, brown). Each stimulus subtended approximately $4.6^\circ \times 4.6^\circ$ of visual angle. The contrast between the stimuli and background screen color was reduced to the point that no visual aftereffects occurred between stimulus presentations. Example stimuli are presented in Figure 1. On each trial within a block, one stimulus was randomly selected, without replacement, to appear in one of the four visual locations on the screen. Thus, on each block, participants were presented with the same stimuli, but the order they appeared between blocks differed. This manipulation to the stimuli was also used to mask the sequence. The stimuli were presented using E-Prime 2.0 software (Schneider, Eschman, & Zuccolotto, 2002).

### 2.3 Data preprocessing and a summary of the dependent variables

#### 2.3.1 Accuracy and RTs from manual responses

Both accuracy and RT were recorded as participants made a manual response on the SRT task. A correct response was
recorded when participants pressed the button on the response pad that matched the location of the visual stimulus. For each participant, the proportion of correct responses was computed for each block (i.e., S1–S5, R6). RT, recorded in milliseconds (ms), measured the time taken to press the correct button on the response pad following stimulus onset. Only RTs from correct responses were included in the analyses. For each participant, the median RT for each block was computed.

2.3.2 | EEG: Recording and data preprocessing

As participants completed the SRT task, EEG was recorded using 20 Ag-AgCl electrodes that were embedded in an elastic cap (EasyCap, Herrsching, Germany). The electrodes were placed in the following positions of the EEG 10–20 system: Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, P8, P3, Pz, P4, P8, O1, O2, and also on the left and right mastoids. Electrooculogram (EOG) was acquired from electrodes placed on the left outer canthus and right outer canthus as well as above and below the left eye. The EEG was acquired using a TMSi RefA system (Twente Medical Systems International, The Netherlands) at a sampling rate of 2048 Hz using a common average as the online reference. Prior to recording, impedances were reduced to below 5 kΩ.

Offline EEG data processing was undertaken using EEGLAB 13.6.5b (Delorme & Makeig, 2004) and ERPLAB 6.0 (Lopez-Calderon & Luck, 2014). The EEG data were first downsampled to 250 Hz and high frequency noise reduced using a 0.1 to 30 Hz FIR band-pass filter. EEG data were then rereferenced to the average of the left and right mastoids. Stimulus-locked epochs were created from the continuous EEG commencing −400 prior to stimulus onset to 650 ms postonset. Epochs with anticipatory eye movements were first identified and rejected from further analysis. This was achieved by analyzing the data acquired from horizontal EOG (HEOG) channels. A DC offset correction was then applied only to epochs from the HEOG channels. An epoch was excluded if voltage exceeded ±50 μV from either of the HEOG channels. This threshold aimed to capture horizontal eye movements initiated before the stimulus appeared. This led to an average rejection of 14% of trials from each block (S1 = 14%; S2 = 14%; S3 = 10%; S4 = 14%; S5 = 13%; R6 = 15%). A one-way repeated measures analysis of variance (ANOVA) revealed no significant effect of block on the number of trials rejected from each block, $F(3.493, 115.272) = 1.240, p = 0.293, \eta^2_p = 0.036$.

Epochs without anticipatory eye movements were baseline corrected using the mean amplitude of the 200 ms prestimulus data. Separate averaged ERP waveforms were computed for each block from the SRT task (i.e., blocks S1–S5 and R6). Removal of further ocular and nonocular artifacts was achieved by running independent components analysis in EEGLAB and then correcting the EEG signal using the ADJUST algorithm (Mognon, Jovicich, Bruzzone, & Bulatti, 2011). An epoch was discarded from further analyses if amplitude exceeded ±150 μV and/or if it was associated with an incorrect manual response. Separate averaged ERP waveforms were computed for each block from the SRT task (i.e., blocks S1–S5 and R6).

Latency ranges for the ERP components were derived using a data-driven procedure outlined by Brooks, Zoumpoulaki, and Bowman (2017). This procedure has been shown to reduce Type I error rates with respect to identifying regions of interest on ERP waveforms. This approach aims to find regions of interest on an ERP waveform while balancing the need to accommodate specific experimental conditions but avoid the problem of overfitting the data. In the context of the current study, this procedure involved computing a grand-averaged ERP aggregated across all trials and conditions. Latency ranges were then defined using this waveform. Aggregate grand averages from trials collapsed across block are presented in Figure 2a. Discriminable P1, N1, and P3 components were found at P7, P3, Pz, P4, P8, O1, and O2 electrode sites. Figure 2a shows the ERP components of interest to be present across left and right electrode sites within the parietal-occipital region. It should be noted that typically the amplitude of P1 and N1 components vary depending upon in which visual field a stimulus appears (Luck & Kappenman, 2012). The symmetrical response of the P1 and N1 components in this study most likely reflect that the visual stimulus appeared an equal number of times in each visual field. Given the distribution of the ERP response across hemispheres and that visual stimuli appeared in both visual fields, data from the midline Pz site were used in the analyses (e.g., Oken, Chiappa, & Gill, 1987).

Mean amplitude was used as the dependent variable for the ERP analyses. P1 and N1 latency ranges for the mean amplitude were computed over a 40-ms window centered on the peak using the aggregate grand average from trials. These peaks are identified in Figure 2b. Using this criterion, the latency ranges for the P1 and N1 were 152–192 ms and 196–236 ms, respectively. Mean amplitude for the P3 component was computed over 280–368 ms time interval. These two values corresponded to two discernible peaks marking durations in which amplitude was highest for this component (see Figure 2b). For each participant, ERP amplitude was averaged over the aforementioned latencies.

2.4 | Statistical analyses

The effect of block (S1, S2, S3, S4, S5, R6) on the behavioral and electrophysiological data was examined using a one-way repeated measures ANOVA. The Greenhouse–Geisser adjustment for nonsphericity was used when appropriate. Next, planned comparisons comprising paired samples $t$ tests were undertaken to examine sequence learning effects. The first

\[ F(3.493, 115.272) = 1.240, p = 0.293, \eta^2_p = 0.036 \]
FIGURE 2  (a) Aggregate grand-averaged ERP waveforms from trials (collapsed across blocks). (b) Aggregate grand-averaged ERP waveforms at Pz site showing peak amplitude for P1, N2, and P3 components
comparison tested for a difference between the first and last sequence blocks (i.e., S1 vs. S5). The second comparison examined whether there was a significant change from the final sequence blocks (S5) to the following random block (R6). For the planned comparisons, observed p values were corrected using the Bonferroni procedure (i.e., unadjusted p values were multiplied by two). For all statistical tests, alpha was set at 0.05.

2.5 | Procedure

Participants were presented with the prescreening instrument, handedness measure, and WASI prior to being administered the SRT task. We assessed implicit learning via self-report. Specifically, after participants completed the SRT task, they were asked whether they were aware that the visual stimulus followed a pattern. Initially, 39 participants were tested for this study. Of this total, four participants indicated that they were aware of the sequence after they completed the SRT task. Data from these participants were excluded from the study. The final sample comprised 35 participants.

3 | RESULTS

3.1 | Behavioral data

3.1.1 | Accuracy and RT from manual responses

The mean proportion of correct responses for all blocks approached ceiling (S1: M = 0.94, SE = 0.01; S2: M = 0.93, SE = 0.01; S3: M = 0.94, SE = 0.01; S4: M = 0.93, SE = 0.01; S5: M = 0.92, SE = 0.01; R6: M = 0.90, SE = 0.01). An arcsine transformation was applied to the data prior to running the analysis to correct for nonnormality. The effect of block (S1, S2, S3, S4, S5, R6) on accuracy was statistically significant, $F(3.771, 128.209) = 5.671, p < 0.001, \eta_p^2 = 0.143$. The first planned comparison revealed that there was no significant change in accuracy from Blocks S1 and S5 ($p = 0.096$). The second planned comparison showed a significant decrease in accuracy from B5 to R6 ($p = 0.006$).

Figure 3a presents summary data reporting RT by block. The general trend observed was a decrease in RT (i.e., faster response times) over the blocks.

![Figure 3](image_url)

**Figure 3** (a) Manual reaction times. (b) Mean P1 amplitude. (c) Mean N1 amplitude. (d) Mean P3 amplitude.
responses) across the sequence blocks (S1–S5) followed by an increase in RT in R6 (random block). The ANOVA revealed a significant main effect of block on RT, $F(4.019, 136.635) = 6.894, p < 0.001, \eta_p^2 = 0.169$. Planned comparisons revealed RT in S5 were significantly faster compared to S1 ($p = 0.023$). There was also a significant increase in RT from S5 to R6 ($p < 0.001$). This pattern of results shows participants’ RT became significantly faster when exposed to the sequence blocks, but then slowed down when random trials were presented.

### 3.2 Analyses of ERP data

Figure 4a shows grand-averaged ERP waveforms for each block. Highlighted in Figure 4b,c,d are peaks for the P1, N1, and P3 components, respectively.

#### 3.2.1 Analyses of mean amplitude

Separate ANOVAs tested the effect of block on the mean amplitude of the P1, N1, and P3 components. For the P1 component, the effect of block on mean amplitude was significant,
F(5, 170) = 2.798, p = 0.019, η^2_p = 0.076. Planned comparisons revealed mean amplitude was significantly lower in S5 compared to S1 (p = 0.012). There was also a significant increase in mean amplitude from S5 to R6 (p = 0.003). This pattern of amplitude change mirrors the RT data. This is seen in Figure 3b, which plots mean P1 amplitude by block.

There was no significant effect of block on mean amplitude for the N1 component by block. While changes in N1 mean amplitude over the blocks are similar to the RT data, the effect of block on N1 mean amplitude was not statistically significant, F(5, 170) = 0.975, p = 0.435, η^2_p = 0.028. Also, both planned comparisons were not statistically significant (S1 vs. S5: p = 0.127; S5 vs. R6: p = 0.125). Figure 3d presents mean amplitude for the P3 component by block. For this component, the main effect of block was also not statistically significant, F(5, 170) = 1.620, p = 0.157, η^2_p = 0.045. There was no significant difference in mean amplitude between S1 and S5 blocks (p = 0.823) or between S5 and R6 (p = 0.282).

4 | DISCUSSION

This study examined attentional-related ERP components associated with implicit sequence learning on a version of the Nissen and Bullemer (1987) SRT task. In the first instance, we found that this task elicited discernible P1, N1, and P3 components. However, unlike the oddball version of the SRT task previously used (Eimer et al., 1996; Ferdinand, Rünger et al., 2010; Miyawaki et al., 2005; Schlaghecken et al., 2000), we did not observe an N2 component. The data indicated that changes in P1 amplitude were sensitive to sequence learning. Analyses showed that RT decreases across sequence blocks (S1–S5) were paralleled by a reduction in P1 mean amplitude. Also, when RT increased from sequence to random blocks (S5–R6), P1 amplitude also increased. Based on this pattern of results, it is suggested that visuospatial sequence learning leads to a decrease in the levels of attention needed to complete the SRT task. This effect is specific to the P1 component and therefore visuospatial attention. Sequence learning effects were not found to significantly influence N1 or P3 mean amplitude.

Increases in P1 amplitude have been proposed to reflect an increase in the allocation of visuospatial attention to a target (Hillyard & Anllo-Vento, 1998). The reduction in P1 amplitude over the sequence blocks (S1–S5) is interpreted to indicate a reduction in visuospatial attention. This reduction was found only to occur after repeated exposure to the sequence. We argue that this modulation is related to sequence learning effects rather than general task demands. An alternative possibility is that changes in P1 amplitude might be due to general arousal level or mental fatigue, given the repetitive nature of the task. However, this proposal does not fit the data because sequence learning effects were not observed for the N1 or P3 components (Luck, 2014). Also, if mental fatigue did cause the reduction in P1 amplitude, it would be expected that this reduction would continue through to the final random block, which was not the case.

The pattern of P1 amplitude change may indicate that sequence learning on the SRT task leads to a reduction in the levels of visual attention. This proposal is in line with the fMRI data presented by Thomas et al. (2004) showing that sequence learning is associated with a decrease in parietal activation. A reduction in attention levels on the SRT task may occur at the same time that the basal ganglia assert greater influence on manual responses. Substantial research shows that basal ganglia support the implicit learning of sequences (Ashby, Turner, & Horvitz, 2010; Bar-Gad, Morris, & Bergman, 2003; Bradshaw, 2001; Hardwick, Rottschy, Miall, & Eickhoff, 2013). Once knowledge of the sequence has been acquired by the basal ganglia, manual responses to the stimulus may become increasingly more automatized. As a consequence, fewer demands are placed on visual attentional resources leading to a decrease in P1 amplitude. On the final random block (Block R6), however, sequence knowledge can no longer be used to provide a correct response to the visual stimulus. This may lead to a greater reliance on visuospatial attentional resources to process the visual stimulus that is reflected by an increase in P1 amplitude. We note that our hypothesized relationship between basal ganglia activation and P1 amplitude will need to be tested in future research using combined fMRI-EEG methodology.

Our finding that sequence learning had a significant effect on P1 but not N1 amplitude is consistent with past research showing these two components reflect different attentional processes (Coull, 1998; Kotchoubey, 2006; Luck & Kappenman, 2012). In previous research, N1 amplitude has been modulated by changing the demands associated with evaluating a characteristic of a visual stimulus (Vogel & Luck, 2000). The nonsignificant main effect of block on N1 amplitude most likely indicates that the demands associated with evaluating the visual stimulus remained constant throughout the task. Thus, a new finding arising from this study is that sequence learning on the SRT task can lead to dissociations between P1 and N1 components.

One limitation of this study is the extent to which sequence learning can be considered implicit. After completing the SRT task, we asked participants to indicate whether they became aware of the sequence. In this study, only those participants who were not aware of the sequence were included in the analyses. Analyses of P3 amplitude provide some evidence that sequence learning was implicit. In previous research, the P3 component has been found to be sensitive to sequence learning effects in groups who explicitly learned the sequence (Ferdinand et al., 2008; Miyawaki et al., 2005;
4.1 Conclusions

This study revealed that the P1 ERP component could be modulated by learning a visuospatial sequence on the SRT task. The implication of this finding is that implicit sequence learning influences visual attention. To our knowledge, this is the first study to identify that sequence learning on the SRT task modulates the P1 component. More generally, the study demonstrates that ERP can be used to study implicit sequence learning on the standard version the SRT task in which sequence and random trials are presented in blocks.

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