Cognitive control modulates the expression of implicit sequence learning: Congruency Sequence and Oddball-dependent Sequence Effects

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Abstract

Implicit Sequence Learning represents an established paradigm to investigate incidental skill acquisition in a laboratory environment. During a covert task, participants respond to the location of a target appearing over a series of locations according to a complex sequence, which gets violated in a reduced set of control trials. Even though participants are not fully aware of the sequence, they respond faster and more accurately to trials following it, thus expressing sequence knowledge. Recent evidence has challenged the view that such knowledge is applied rigidly and affects performance independently from control influences. Jiménez et al., (Consciousness and Cognition, 18(3), 690-700, 2009) highlighted that its expression gets reduced immediately after trials not conforming with the learned sequence – an effect that resembles the Congruency Sequence Effect (CSE) commonly observed in interference tasks. However, such effects can also be alternatively explained in associative terms. In this experimental series we took advantage of the well-known attentional properties of oddball sounds and introduced them as an orthogonal variable with respect to the learning process. We found that oddball sounds also hindered the automatic expression of sequence learning, highlighting an Oddball-dependent Sequence Effect similar to the CSE, but most clearly triggered by cognitive control. We also tested some corollary hypotheses of the alternative associative account, showing that the CSE is also obtained when controlling the impact coming from negative priming or associative learning confounds.

Keywords: implicit sequence learning, cognitive control, congruency sequence effect, oddball effect

Public Significance Statement: The current work suggests that control processes modulate the expression of learning, even if automatic and unconscious.

Cognitive control modulates the expression of implicit sequence learning: Congruency Sequence and Oddball-dependent Sequence Effects

When you practice a sport, interact with any technological device, or simply tie your shoelaces, you are continuously improving the way in which you do these tasks, even though you don't explicitly attempt to commit your experience to memory, and you may not be aware of learning anything from that practice. Implicit sequence learning represents the set of processes through which participants incidentally acquire such procedural knowledge, and the Serial Reaction Time (SRT) task, developed by Nissen and Bullemer (1987), has become a standard model of this learning. The SRT task is typically a four-choice reaction time task in which participants are required to localize the position of a stimulus appearing at one of four possible locations, by pressing the corresponding key. Unbeknownst to participants, the stimulus presentation occurs according to a sequence of positions, which they learn throughout training, as indexed by faster reaction times (RTs) whenever the target is presented accordingly (i.e., training trials from here on), and increased RTs and decreased accuracy whenever presented randomly or following a different control sequence (i.e., control trials from here on).

Control of automatic expression of implicit sequence learning

Recent studies have shown that the expression of such learning can be flexibly modulated by contextual changes demanding for increases in cognitive control. Jiménez et al., (2006) observed that, after training with the standard SRT task, the expression of learning disappeared when participants were transferred to a more control demanding condition and were asked to localize the position of the target accompanied by three distracters (Experiment 2, incidental learners). In another experiment (Vaquero et al., 2019, Experiment 1), participants were first trained with the target presented among distracters, and then were transferred to a simpler localization task with the target alone, without distracters. As expected, during these transfer blocks mean RTs decreased (from around 500 ms to 400 ms), and more importantly, sequence learning was still solidly expressed. A set of follow-up experiments, which trained participants under different conditions and then transferred them either to a more or to a less control demanding context, confirmed that participants were able to transfer their knowledge toward those conditions with decreased control demands, whereas the expression of learning was specifically hindered when transferred to a context requiring higher control. Similarly, Toh and colleagues (2021) have recently shown that implicit sequence learning was absent in a conjunction search task requiring high control demands, whereas it was expressed when control demands were reduced.

Other studies suggest that the expression of sequence learning can also be affected by more transient, trial-by-trial modulations that resemble the effects usually attributed to reactive cognitive control (Braver, 2012). For instance, once learning is acquired in a probabilistic version of the SRT task, the expression of learning seems to be flexible enough to be modulated by the sequential nature of the immediately previous trial, thus leading to an effect analogous to the congruency sequence effect (CSE) commonly observed in interference tasks (Braem et al., 2014; Duthoo et al., 2014a, 2014b; Egner, 2007). Indeed, Jiménez et al., (2009) trained participants with a probabilistic version of the task, in which the location of the target on each trial conformed either to a training sequence or to an equally complex control sequence. As shown in Figure 1, the two alternative sequences were structurally analogous (i.e., one sequence was created from the other by replacing the 1st position with the 3rd one), and they equally conveyed second order conditional information (Reed & Johnson, 1994; Schvaneveldt & Gomez, 1998), meaning that the legal successor was completely determined by the two previous locations. The authors observed that after extensive training in which 90% of the trials conformed to the training sequence and the remaining 10% followed the control sequence, robust learning was observed. However, when trials were classified as preceded by a control vs. a training trial, results showed that sequence learning was mostly expressed after training trials, but was hindered after infrequent control trials (Figure 2A). This result was interpreted according to the conflict monitoring account proposed by Botvinick et al., (2001), as suggesting that the violation of a predicted stimulus location triggered by a control trial set off conflict and increased attentional control, thereby decreasing participants' reliance on their implicit knowledge on the following trial. A similar pattern of results has been observed specifically for perceptual and motor sequence learning (D'Angelo, Jiménez et al., 2013; D'Angelo, Milliken et al., 2013), therefore replicating and extending what seems to be a quite solid result. Note that, in contrast with more classic interference tasks, in which participants' expectancies and conflict rely mostly on explicit representations, reliable CSE has been also observed from conflict elicited without awareness (van Gaal, et al., 2010). Similarly, the literature on the Context Specific Proportion Congruence (CSPC) effect has also shown that participants can learn implicitly about the association between a specific context and the proportion of congruency associated to it, and automatically apply more or less control as a function of the learned association (Braem, et al., 2019; Crump et al., 2006). Therefore, we surmise that also in the context of sequence learning, a modulation of trial-by-trial reliance on sequence knowledge can occur whenever sequence expectations are violated, even if these expectations remain implicit.

Alternatively, some authors have proposed a more parsimonious explanation of the CSE in the SRT task, sustaining that it could emerge from learning higher than second order contingencies in the training sequence, rather than arising from an increase in cognitive control following conflict detection (Beesley et al., 2012). If training can produce learning of third- and larger-order contingencies, the presentation of a training trial after a larger set of previous training trials would maintain it (as in T-T transitions), whereas interspersing a control trial would break the associative chain and impair performance (as in C-T transitions). Beesley et al., simulated the CSE with a Simple Recurrent Network (SRN) based on associative learning mechanisms (Figure 2B), and showed that the magnitude of the effect depended on the amount of training. Moreover, their re-analysis of the data in Jiménez et al., (2009) confirmed that the CSE appeared at a later point of training, while it was not significant when learning was first expressed. In addition, the authors re-analyzed data from a previous study with a higher power compared to Jiménez et al., and observed that the empirical CSE (Figure 2C) converged (in time and shape) with the model predictions, thus indirectly supporting the hypothesis that associative learning of third or larger-order sequential contingencies could explain these results.

Cognitive control and unexpected events

As previously stated, the CSE observed in the context of probabilistic sequence learning was interpreted by Jiménez et al., (2009) as showing an increase in control after an unexpected event in the sequential regularity. Notably, the unexpected event in the SRT task is a task- and sequence-relevant trial, rather than a competing but irrelevant feature of the display, as it is the case in interference paradigms. As such, one could wonder whether the expression of sequence learning, as an instance of automatic behavior, could also become flexibly modulated by the presence of other types of salient but task- and sequence-irrelevant changes.

One way to investigate the effects of unexpected environmental changes on information processing has been the Oddball paradigm (Parmentier, 2008, 2014, 2016). In the classic tone duration discrimination task, participants have to discriminate between equally likely short and long tones, which are presented on the majority of the trials with a standard pitch (e.g., 90% 1000 Hz) but change to a different pitch on the remaining trials (e.g., 5% 950 Hz, 5% 1050 Hz). Even though irrelevant for the primary task, the pitch deviance from the standard regularity induces deviance distraction (i.e., oddball effect), as reflected in delayed response times and, sometimes, an increased error production in the primary task (Escera et al., 1998; Berti & Schröger, 2003). Electrophysiological studies confirmed that the brain encodes and represents the regularity of the inter-pitches relationships and uses such representations to predict incoming information. Whenever an unexpected deviant sound is presented, it mismatches the predictive model of the acoustic regularity, resulting in a MMN component. Such violation of expectations represents a signal for attention switching toward the deviant distractor (Kimura, Schröger, & Czigler, 2011; Kimura, Widmann, & Schröger, 2010; Winkler, 2007), which produces a late P3a component reflecting an attentional interruption recruiting frontal areas. Moreover, when participants are engaged in a primary task, the task-irrelevant deviance automatically initializes a change of response, which triggers conflict if the task-relevant feature requires a repetition of responses (Roeber et al., 2005). Therefore, it has been shown that a later frontal negative deflection (RON) signals both the initial attention reorientation towards task goals (early RON) and the engagement in cognitive control processes to resolve such conflict (Berti, 2008). The involvement of cognitive control processes in auditory distraction was further supported by neuroimaging findings of left medial frontal gyrus and cingulate giri activations during task-irrelevant pitch changes (Rinne et al., 2007).

The interaction between deviance distraction and cognitive control mechanisms has been directly addressed by a previous study (Leiva et al., 2015), which explored the impact of novel sounds (e.g., short clips of environmental sounds such as drill, hammer, telephone ring) compared to standard (600 Hz) tones on Go/Nogo task performance. When the novel sounds anticipated Nogo trials, Nogo performance was enhanced (i.e., fewer commission errors), confirming the protective role of cognitive control engagement. On the contrary, when sounds did not convey any information on the subsequent trial type, the novel sounds increased response times to Go trials and commission errors to Nogo trials. Therefore, it appears that there is a reciprocal relation between control and deviance distraction, in which the engagement of control protects the system from deviance distraction, but deviance distraction impairs performance in the context of a controlled task set.

Aim of the experimental series

The main purpose of this work was to explore whether transient cognitive control processes modulate the expression of sequence learning beyond the influence of associative learning of third- or larger-order associations (Beesley et al, 2012). For this purpose, we combined the SRT task with the Oddball paradigm, and we presented unpredicted oddball sounds during the acquisition (Experiment 2) or the expression (Experiment 1 and 2) of sequence learning. Oddball sounds are characterized by specific attentional properties (Berti, 2008) and, unlike control trials, their presentation was orthogonal (i.e., task-irrelevant and sequence-irrelevant) to the associative learning process. For this reason, we could measure their effect on modulating the acquisition and the expression of sequence knowledge irrespective of possible associative learning confounds.

A secondary purpose was to replicate the CSE observed in Jiménez et al., (2009) with a noisier SRT task (i.e., 80% instead of 90% training trials), in order to minimize the effect of learning third- or larger-order contingencies on CSE. To further test whether the CSE obtained with 80% training trials could be explained in purely associative terms, we conducted a (non-preregistered) replication of the simulation reported by Beesley et al. (2012) and directly compared the CSE obtained by exposing the model to either 90% training trials (as in Beesley and colleagues) or to 80% training trials (as in the current set of experiments).

Experiment 1

In order to address the effect of irrelevant and unexpected events on the expression of sequence knowledge, we combined the SRT task with the Oddball paradigm in a cross-modal

SRT-Oddball task. Over the first trial blocks, participants performed a probabilistic visual SRT in conditions in which the target trial was always preceded by an irrelevant standard sound. Then, when learning was achieved, they were presented with a number of blocks in which training and control trials could be preceded by either standard or deviant sounds. Given that deviant sounds are known to capture attention (i.e., deviance distraction, see Parmentier 2014, 2016), and that similar abrupt changes have impaired cognitive control (Leiva et al., 2015), one might predict that the inclusion of such deviant sounds could result in an increased expression of the automatic response tendencies underlying sequence learning. However, oddball sounds could actually decrease the expression of sequence learning due to the active re-orientation of attention toward task goals and engagement in control processes following deviance distraction (Berti et al., 2008; Roeber et al., 2005). Upregulation of control could also occur due to the conflict instantiated between the expected (standard) sound and the presented (oddball) sound (Botvinick et al., 2001), and likewise reduce the expression of any automatic response tendency (Jiménez et al., 2009). Since these two opposite predictions are compatible with some previous results, we adopted an exploratory stance in our first attempt of merging the SRT and Oddball paradigms. These hypotheses together with the predicted and the exploratory plan of analyses were preregistered in Open Science Framework before data collection (https://osf.io/enpvk).

Method

Participants

The sample size was determined on the basis of power calculation for a similar experiment (https://osf.io/dq6fn/). To perform the a priori power analysis with G*power 3.1 (Faul et al., 2009), we considered the effect size (η_p^2 =.26) of the CSE observed in Jiménez et al., (2009), given that the oddball effect on learning expression represents a sequential effect as well. The analysis revealed that at least twenty-three participants per group were necessary to observe a sequential effect, with 1-β = .90, α = .05, and a correlation among repeated measures of 0.6. Thus, twenty-four students (3 males, M_{age}=19.58, SD_{age}=2.60) from the University of Granada, which had never participated in similar experiments before, took part in this experiment in exchange for course credits. The experiment was part of a larger research project approved by the Universidad de Granada Ethical Committee (536/CEIH/2017).

Apparatus and materials

The sequence of stimuli composing the SRT task was presented on a 14-inch computer screen through the INQUISIT 4.0 software. The participants used a keyboard to respond to stimuli by pressing one of four response keys mapped into the four possible stimulus positions. The sequence used to generate the targets were two complementary SOC sequences (Schvaneveldt & Gomez, 1998), each composed by a series of twelve locations: labeling the four positions on the screen from left to right as 1, 2, 3 and 4, respectively, the position of each target followed the sequence 1-2-1-4-3-2-4-1-3-4-2-3 for SOCa, and the series 3-2-3-4-1-2-4-3-1-4-2-1 for SOCb (Figure 1A).

Procedure

The experimental procedure followed a within-subjects design and consisted in a training phase (blocks 1-8), an oddball phase (blocks 9-11), a re-training phase (blocks 12-13), and a final block including a direct measure of sequence knowledge in the form of a cued generation task (block 14). In the SRT task, (blocks 1-13), participants localized a target letter “X” appearing over one of four placeholders along the horizontal axis of a computer screen (Figure 1B), by pressing the spatially corresponding Z, X, N, or M keys on a QWERTY keyboard. Unbeknownst to the subjects, the target was presented through a probabilistic trial-by-trial presentation procedure according to one SOC sequence on 80% of the trials, and following the other SOC sequence on 20% of the trials. As shown in Figure 1A, all first-order transitions occurred evenly in both sequences, but the successor of these transitions discriminated perfectly between them. For instance, the path 2-4 (i.e., first-order transition) can occur in both sequences, but this context predicts location 1 as the successor in the case of SOCa (i.e., 2-4-1 being the second-order transition), and location 3 in the case of SOCb (i.e., 2-4-3 being the second-order transition). The specific status of SOCa and SOCb as training or control sequences was counterbalanced across participants.

During the initial training blocks (1-8), an irrelevant standard tone (i.e., 150 ms duration of a sine wave tone with a 600 Hz frequency) was delivered through headphones 250 ms before the “X” visual targets. The visual target was presented above the placeholder until response, followed by a 100 ms post-trial pause, thus achieving an ISI between visual targets of 350 ms. Incorrect responses were signaled by visual feedback consisting in a flashing screen, followed by a 500 ms pause. During the oddball blocks (9-11), participants kept performing the SRT task in the same conditions, but a higher pitch deviant tone (i.e., a sine wave tone of 150 ms with a frequency of 710 Hz) replaced the standard tone on 20% of the trials, thus introducing the oddball manipulation. In blocks 12-13, participants performed again the SRT task with just standard tones, so as to restore the learning conditions before introducing a direct measure of sequence knowledge. During block 14, we included a cued generation task as a measure of the extent to which learners were able to directly discriminate between the training and control successors of each possible subsequence. The methodology and the results of the cued generation task are described in the Supplementary materials.

Results

All the planned and exploratory analyses were performed with JASP software (2018) after collecting the data from all the subjects (*N*=24). Following our preregistered plan of analyses (https://osf.io/enpvk), for each participant and each block, valid RTs were computed by excluding the first two trials of each block (1.67 %) as well as the incorrect responses (3.38 %). Then mean RTs were calculated, the trials with RTs smaller or larger than three standard deviations from the mean were eliminated (1.40%), and the trials preceded by an error and those preceded by a control trial were excluded from the main analysis, to avoid post error slowing and sequential effects. In order to compute the percentage of correct responses, the first two trials of each block and the trial preceded by a previous control trial were also excluded from the main analysis. No participant was excluded due to an accuracy criterion, as all of them performed above the exclusion criterion of 90% per block (mean accuracy 96.50%). RTs for correct responses and percentage of accuracy were computed separately for training and control trials.

Sequence learning

As shown in Figure 3, and confirmed by the Block (8; 1-8) x Trial type (2; training vs. control) repeated measures ANOVA, participants acquired sequence learning, as they responded faster on training compared to control trials, Trial type, $F(1,23)=23.045$, $p<.001$, $\eta_p^2=.50$. There was no tradeoff between RTs and accuracy measurements, as participants produced more errors in response to control trials, Trial type, $F(1,23)=13.903, p=.001$, $\eta_p^2=.38$.

As reported in Figure 4A, during the oddball blocks, the Sound type (2; standard vs. deviant) x Trial type (2; training vs. control) repeated measures ANOVA showed a significant increase in RTs to training trials and reduced the expression of the automatic ISL after deviant sounds, Sound type x Trial type, $F(1,23)=4.737$, $p=.04$, $\eta_p^2=.17$. The same effect was not significant for the measures of accuracy, $F(1,23)=1.882, p=.18$. To analyse whether the effect of deviant sounds did affect performance continuously over the oddball blocks, or whether it resulted from an initial surprise, that would be offset with practice, we conducted a non-preregistered analysis of this effect over successive blocks. The overall analysis highlighted a main effect of Sound type, $F(1,23)=6.478$, $p=.02$, $\eta_p^2=.22$, and the Block x Sound type interaction fell short of significance, $F(2,46)=2.797, p=.07$, $\eta_p^2=.11$, with a deviance distraction effect of 27 ms during block 9, which then decreased to 7 and 10 ms during blocks 10 and 11, respectively.

Congruency Sequence Effect

The analysis of the CSE was performed by means of a Previous Trial type (2; training vs. control) x Trial type (2; training vs. control) repeated measures ANOVA conducted on the later training blocks, including the same number of blocks preceding and following the oddball blocks (i.e., blocks 7-8 and blocks 12-13). As shown in Figure 5A, the CSE was significant, Previous Trial type x Trial type, $F(1,23)=4.524$, $p=.04$, $\eta_p^2=.16$.

Discussion

As expected, participants learned the sequence, resulting in faster and more accurate responding to training trials as compared to control trials. Interestingly, and in line with the oddball literature, the deviant sound violated the regularity of the standard sounds and impaired performance, but it modulated responding selectively to training trials, while control trials remained unaffected (Figure 4A). The absence of modulation over RTs to control trials could be explained by a blend between two opposite effects. On the one hand, the attentional capture induced by deviant tones (Berti & Schröger, 2001) could have affected negatively both training and control trials. On the other hand, deviance distraction could have also provoked an increase in attentional control (Berti et al., 2008; Botvinick et al., 2001; Roeber et al., 2005), which decreased the (facilitatory) impact of automatic response tendencies acquired through sequence learning, but also removed any potential cost provoked by such tendencies when responding to unpredicted control trials.

Overall, oddball sounds modulated learning expression in a similar fashion to the CSE (i.e., oddball-dependent sequence effect, OSE), but the presence of an oddball effect mainly in the first oddball block highlights specific features of this effect. To see whether oddball sounds affect learning and performance differently when presented from the beginning, Experiment 2 included a condition in which deviant sounds anticipated the targets already in the training phase. In addition, since a previous experiment failed to replicate the OSE (see Experiment 2b in Supplementary materials), we employed a stronger deviance manipulation to increase the saliency of oddball sounds.

Experiment 2

The aim of this experiment was to replicate the oddball effect on the expression of sequence learning, and to explore its impact on the acquisition of that learning. If deviant sounds enhance cognitive control (Berti, 2008; Botvinick et al., 2001; Jiménez et al., 2009), we would observe an OSE even after a repetitive presentation of the deviant sound over the whole training phase. However, the effect could be reduced if participants integrate this variable feature of their task while learning the sequential regularities. Moreover, we aimed to replicate Experiment 1 with a more salient deviant sound, in order to elicit a stable deviance distraction and observe its effect on ISL acquisition and expression. The hypotheses as well as the predicted plan of analysis were preregistered on Open Science Framework (https://osf.io/px5tf).

Method

Participants

Consistent with the power analysis reported in Experiment 1, 48 students from the University of Granada, who had never participated in similar experiments before, were recruited for this experiment in exchange for course credits, being randomly assigned to the Standard (n=24, 4 males, M_{age}=20.17, SD_{age}=1.97) or the Standard/Deviant group (n=24, 7 males, M_{age}=20.83, SD_{age}=2.92). The experiment was part of a larger research project approved by the Universidad de Granada Ethical Committee (536/CEIH/2017).

Apparatus and materials

The apparatus as well as the sequence material were the same as in Experiment 1.

Procedure

The experiment followed a between-subjects design with a Standard and a Standard/Deviant group undergoing two different learning acquisition procedures (blocks 1-8), but the same testing blocks (blocks 9-11 and blocks 12-14) and cued generation task (block 15). During the initial training blocks (blocks 1-8), the Standard group performed the SRT task with just standard tones (i.e., 600 Hz sounds) anticipating the visual targets, whereas the Standard/Deviant group was presented with a standard tone on 80% of the trials, and a deviant tone (i.e., 150 ms of white noise) on the remaining 20% of the trials. During testing oddball blocks 9-11, both groups performed the task with the oddball manipulation (i.e., 80% standard sounds and 20% deviant sounds), and during testing standard blocks 12-14 both groups performed the SRT task with just standard sounds. The timing properties of both visual and auditory stimuli across the blocks were the same as in Experiment 1, except that white noise was used as deviant sound instead of a 710 Hz sound. The testing blocks (blocks 9-14) were designed to allow a direct comparison between two groups trained differently, either with 100% standard sounds (Standard group) or with 20% deviant sounds (Standard/Deviant group). Blocks 9-11 assessed the effect of the group manipulation on the OSE. Blocks 12-14 assessed the effect of the group manipulation on the expression of learning under standard conditions. During block 15, both groups performed a cued generation task. The results of the cued generation task are described in the Supplementary materials.

Results

All the planned analyses were performed with JASP software (2018) after collecting the data from all the subjects (*N*=48). The applied filters were the same used in Experiment 1, with 1.67% of the trials representing the first two trials in each block, 4.20% being the remaining incorrect responses and 1.34% the outliers. Mean accuracy was on average 95.7%, therefore data from all participants was considered for the planned analyses.

Implicit Sequence Learning

Figure 6A-B shows RTs of trials preceded by standard sounds in the first 8 training blocks and the last 3 testing standard blocks in both groups. The analysis on training blocks confirmed the acquisition of sequence learning with faster responses to training compared to control trials, Trial type, $F(1,46)=25.482, p<.001, \eta_p^2=.36$, independently of Group, $F<1$. The participants became also overall faster with practice, Block, $F(4.648,213.820)$[1]$=15.171, p<.001, \eta_p^2=.25$, but this resulted in overall decreased accuracy across training, Block, $F(7,322)=9.031, p<.001, \eta_p^2=.16$. The increase in error rate was mainly expressed on control compared to training trials, highlighting learning acquisition in terms of accuracy as well, Trial type, $F(1,46)=28.218, p<.001, \eta_p^2=.38$, and again independently of Group, $F<1$.

We further analyzed learning acquisition during training in the Standard/Deviant group by the means of a Block (8; 1-8) x Sound type (2; standard vs. deviant) x Trial type (2; training vs. control) repeated measures ANOVA. The analysis on RTs confirmed the acquisition of sequence learning, Trial type, $F(1,21)=15.190, p<.001$, as well as a practice effect across time Block, $(7,47)=10.865, p<.001$. As expected, there was an increase in RTs in trials featuring a deviant sound as compared to those presenting a standard sound (i.e., an oddball effect), Sound type, $F(1,21)=13.293, p=.002, \eta_p^2=.39$, but it did not modulate learning across these blocks, Sound type x Trial type, $F(1,21)<1$. The analysis on error rates confirmed the presence of sequence learning, Trial type, $F(1,23) = 12.172, p=.002$ and the practice effect, Block, $F(7,161)=4.051, p<.001$. However, the oddball effect was not significant, Sound type, $F(1,23)=2.685, p=.11$, and it did not modulate the acquisition of sequence learning, Sound type x Trial type, $F(1,23)=3.135, p=.09$, although the descriptive statistics suggested a tendency to make more errors specifically in control trials that included a deviant sound.

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[1] Huynh-Feldt correction for violation of sphericity assumption.

As for the effect of training with or without deviant sounds on the expression of sequence learning under standard conditions, the analysis over blocks 12-14 indicated that learning was expressed in both groups, as reflected by the effect on RTs, Trial type, *F*(1,46)=93.964, p<.001, η_p^2 =.67, and error rates, Trial type, *F*(1,46)=30.267, p<.001, η_p^2 =.40. These effects were not different in terms of Group (both *F*s <1).

A Group (2; Standard vs Standard/Deviant) x Sound type (standard vs. deviant) x Trial type (training vs. control) mixed ANOVA analyzed the effect of training with or without deviant sounds over participants' performance on the testing oddball blocks (9-11). As can be observed in Figure 6C-D, the deviant sound modulated the expression of learning, Sound type x Trial type, *F*(1,46)=6.608, *p*=.01, η_p^2=.13, similarly in both groups, Group x Sound type x Trial type, *F*<1, despite inducing a larger oddball effect in the Standard group, Sound type x Group, *F*(1,46)=9.830, *p*<.01, η_p^2=.18. The OSE was observed in error rate as well, Sound type x Trial type, *F*(1,46)=8.528, *p*=.005, η_p^2 =.16, showing that the deviant white noise increased the percentage of errors in response to control trials similarly in both groups, Group x Sound type x Trial type, *F*<1 (see Figure 7). In addition, a non-preregistered Group (2; Standard vs Standard/Deviant) x Block (3; 9-11) x Sound type (standard vs. deviant) mixed ANOVA further characterized the course of the OSE across the oddball blocks. The analysis suggested that the oddball effect, Sound type, *F*(1,46)=23.087, *p*<.001, η_p^2 =.33, was qualified by a three-way Group x Block x Sound type interaction, *F*(1.760,80.970)[2] =5.053, *p*=.01, η_p^2 =.09. This interaction showed a larger OSE for the Standard group and particularly during the first testing oddball block (i.e., block 9; oddball effect of 36 ms). The same comparison in terms of accuracy

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[2] Huynh-Feldt correction for violation of sphericity assumption.

revealed a significant oddball effect in both groups, resulting in decreased accuracy in trials with a deviant sound, Sound type, $F(1,46)=4.440$, $p=.04$, $\eta_p^2=.09$.

Congruency sequence effect

The CSE was significant during the testing oddball blocks (9-11), Previous Trial type x Trial type, $F(1,46)=6.514$, $p=.01$, $\eta_p^2=.12$, and it was significant in the analysis combining the blocks previous and posterior to them (i.e., 6-8, 12-14), Previous Trial type x Trial type, $F(1,46)=8.571$, $p=.005$, $\eta_p^2=.16$, see Figure 4C.

Discussion

The results of this study showed that Standard and Standard/Deviant groups expressed learning similarly despite the different training conditions (only standard sounds vs. a combination standard and deviant sounds during blocks 1-8). A closer inspection of performance in the Standard/Deviant group during training revealed a significant oddball effect, but deviant sounds increased RTs similarly to training and control trials (although a tendential modulation of learning was observed in error rates, as participants appeared to commit more errors in control trials preceded by deviant sounds). When both groups were presented with the oddball manipulation (blocks 9-11), the oddball effect in terms of RTs appeared to be reduced in the Standard/Deviant group, as these participants had already experienced the oddball manipulation during the previous blocks, a result that is consistent with evidence of habituation to repeated oddball stimuli (Ravden & Polich, 1998). However, participants did not completely habituate to them, because oddball sounds modulated sequence learning in accuracy and RTs measures similarly in both groups.

During blocks 9-11, both groups presented a twofold modulation of sequence learning by deviance distraction: oddball sounds increased error rate to control trials, and decreased the expression of sequence learning in RT (mainly in terms of increased RT to training trials, as in Experiment 1), thereby replicating the OSE (compare panels A and B in Figure 4). Therefore, oddball sounds showed an apparently opposite effect on the expression of sequence learning, as it decreased expression in RTs, but increased it in accuracy).

The OSE in RTs can be explained by taking into account the attentional properties of oddball sounds, which are known to induce both a distraction toward the unexpected event (Escera et al., 1998), but also a reactive increase in attentional control (Berti, 2008). Deviance distraction slowed down responses to both training and control trials, but the subsequent increase in attentional control, which arguably reduces the automaticity of the task, further increased RT to training trials (i.e., cumulative effect), but decreased RT to control trials (i.e., net null effect). This explanation is further supported by comparing the oddball-dependent sequence effect in the two groups (Figure 6C-D): as expected, the deviance distraction component drives the effect in the Standard group (novel to the oddball manipulation) but not in the Standard/Deviant group (less sensitive to the oddball manipulation).

Regarding the OSE in accuracy, previous studies (Berti et al., 2004; Escera et al., 1998; Leiva et al., 2015) have shown that deviance distraction can also increase error rates. For instance, in Leiva et al., the task-irrelevant novel sounds did not only delay RTs to Go trials, but also increased commission errors after Nogo trials, as a consequence of deviance distraction. In the SRT task, training trials would resemble Go responses, while control trials would trigger a tendency to inhibit, or at least override the automatic response tendencies, as it occurs in Nogo trials. Therefore, the increased learning expression in accuracy could represent an increased tendency to produce commission errors after deviance distraction. Alternatively, the effect could be explained by the warning property of (deviant) sounds, which may trigger a non-specific activation that prepares the system for the imminent response (Posner et al., 1980). Callejas et al., (2005) found that the presentation of an auditory warning cue before a spatial cue speeded up the orienting system, so that participants were faster in detecting a target in the cued location compared to a condition without a cue. However, the (beneficial) effect of warning cues on response preparation came at the expense of a reduced efficiency of the executive control network. Thus, the authors concluded that warning cues alert the system to produce a faster orienting to salient stimuli, but prevent control processes from taking part in such processing. In the context of the SRT task, infrequent deviant tones may also work as salient warning cues which fasten RTs but also increase error rate, for their inhibitory effect on executive attention. Crucially, warning cues would increase error especially in response to control trials, in which the appropriate response does not coincide with the automatic response. In line with this interpretation, an error RTs analysis confirmed that participants' error responses were faster compared to correct responses after both warning cues, $F(1,44)=37.088$, $p<.001$, $\eta_p^2=.46$, and that learning expression was different in correct and error RTs, $F(1,44)=20.321$, $p<.001$, $\eta_p^2=.32$. Crucially, post-hoc tests revealed that the expression of learning reversed during error RTs, since participants had the tendency to respond faster when committing an error in response to control trials as compared to training trials, $t=-2.444$, $p=.03$. However, the two different sounds did not significantly modulate error RTs: even though deviant sounds induced faster mean error RTs in response to control trials than in response to training trials, the difference was masked by the high variability in RTs, due to the few incorrect training trials. Indeed, these analyses excluded twenty subjects, because many of them did not produce any error in some of the conditions. Nevertheless, it seems that participants made fast errors in response control trials after both warning cues, but error responses were tendentially faster after deviant warning cues.

In sum, the current study replicated the existence of the OSE (cf. Experiment 1, see Figure 4A-B), suggesting that when an unexpected environmental change occurs, cognitive control may reduce automatic and fast reactions to the incoming stimuli, but that such reductions take time, resulting in either slower and controlled correct RTs or in fast and uncontrolled error responses. This effect paralleled the classic CSE, which arose uniformly after sufficient training.

General discussion

Control of the automatic expression of sequence learning

Oddball-dependent Sequence Effect

The main contribution of this experimental series concerns the combination of the SRT task with the Oddball paradigm as representing a potentially fruitful convergence between different research lines on implicit sequence learning, deviance distraction and cognitive control. The oddball manipulation was successful and highlighted an OSE in both experiments, where the deviant sounds reduced the expression of sequence learning on the following trial. When the difference between standard and deviant sounds was only a difference in pitch (600 vs. 710 Hz, in Experiment 1), the effect was reduced to the first oddball block, thus resulting in an overall small deviance effect which nevertheless modulated sequence learning (but see Experiment 2b in Supplementary materials). More salient deviant sounds (white noise, in Experiment 2), instead, produced a complex set of effects on the expression of sequence learning. First, due to their warning properties (Callejas et al., 2005) and in line with the attentional capture by the distractor (Leiva et al., 2015), deviant sounds triggered fast automatic responses, which increased commission errors in response to control trials. Second, during correct responses, deviant sounds reduced the expression of sequence learning likely due to their effect on attentional control (Berti, 2008) and in line with the conflict monitoring account (Botvinick et al., 2001). According to this account, deviant sounds produced a violation of participants' expectancies, which generated conflict and a subsequent enhancement of cognitive control. Crucially, the oddball manipulation was orthogonal to the sequential information embedded in the SRT task, but the increase in control reduced the expression of sequence learning, by decreasing both the automatic response facilitation to predictable training trials, and their potential interference on responding to control trials.

Alternatively, one might suggest that the standard tone became integral part of the learning process, given that it represented the context for the training sequence on most of the trials. Presenting deviant sounds would then irremediably impair performance on training trials because of the change of context, not because of control mechanisms. However, Jiménez et al., (2006; 2019) have shown that not every change of context impairs the expression of sequence learning, but only those changes towards more control-demanding contexts (see also Toh et al., 2021). Indeed, deviant sounds are characterized by well-defined attentional properties, such as the increase in attentional control after distraction (Berti, 2008). Moreover, if the association between standard sounds and sequential information played a role, we should have observed an increased OSE in the Standard group compared to the Standard/Deviant group, which was not the case. As such, the outcomes of the SRT-Oddball task can be thoroughly explained by the control account and indicate that the expression of sequence learning can be modulated by reactive changes in cognitive control.

Congruency Sequence Effect

The second purpose of this experimental series was to replicate the CSE observed in Jiménez et al. (2009) with a noisier training procedure (i.e., 80% instead of 90% training trials), which would reduce the impact of associative learning on the emergence of the CSE (Beesley et al., 2012). Previous computational work carried out by Beesley and colleagues, provided convincing evidence that the SRN - an associative model of learning devoid of any control mechanism - was able to reproduce the CSE when exposed to 90% training trials, and suggested that the same learning mechanisms would more parsimoniously explain the CSE also in natural learning systems, with no need to call in cognitive control. Since we observed a consistent CSE in the current set of experiments (with 80% training trials), we analysed whether a SRN would still be able to reproduce CSE when exposed to the same training conditions. For this reason, we run two separate simulations and we exposed one model to 80% training trials (and 20% control trials, as in in the current experiments; $SRN_{80:20}$ from here on), and compared the learning outcomes (i.e., sequence learning and CSE) with a model trained with 90% training trials (and 10% control trials, thereby replicating Beesley et al.; $SRN_{90:10}$ from here on).

As described by Elman (1990), the SRN is a backpropagation multi-layer network with a recurrent loop that allows the state of the hidden layer on each trial to be copied over a context layer, that in turns affects the activation of the hidden units over the upcoming trial, behaving just as an additional set of input units (see Figure 8). One of the key aspects of sequence learning in the SRN is that only the information about the current trial can be locally represented in the input, whereas all other information concerning previous trials cannot be represented at face value, but rather should be maintained as a "prediction state" distributed over the context layer. This means that any previous state must be "prediction relevant" at each stage for its representation to shape the hidden layer' state, and hence to get represented as an effective context (Jiménez et al., 1996). In the case of the structures arranged in the present experiments, in which any successor becomes optimally predicted by a series of two preceding trials, and in which going further back does not improve its predictability, one might expect that the model would have much trouble to represent the information coming from these farther trials, especially in highly noisy contexts. Therefore, our modelling work aimed at exploring whether this long-run sensitivity could be equally observed when the proportion of control trials increased from 10 to 20 % of the trials.

To maximise the learning capacity and representational power of both models, we chose the largest values of the parameters explored by Beesley et al., (2012), although we run only 50 instead of 100 independent simulations for each set of parameters, relying on their observation that the variance between individual simulations was so small as to make error bars imperceptible. Therefore, each SRN model was trained with .5 learning rate, and it consisted of 4 input units, 150 hidden units, 150 context units that copyback the activation of the hidden units over the previous trial, and 4 output units that represent the model's prediction for the upcoming trial. On each trial, the activation of the input unit representing the current location was set to 1, while all remaining input units were set to 0. Weights were randomly initialised within the range -.5 to .5, and bias units connected to both hidden and output units, with their weights initialised within the same range. Both the input, activation, and learning functions followed those described in Beesley et al. To compute delta values, we also followed their lead, reducing the target output activations to .1 and .9 instead of using 0 and 1, to make these output predictions more reachable (Rumelhart & McClelland, 1986). On each trial, the prediction of the model was measured as the Luce Choice Ratio (LCR), which amounts to the activation of the target unit divided by the sum of the activation over the four output units. To mimic learning effects on reaction times, we also inverted this measure, using 1-LCR as the measure of learning. To reproduce as close as possible the learning conditions of the current set of experiments, each SRN model was exposed to 13 training blocks, each consisting of 120 trials generated probabilistically, as described above. The simulations were run on MatLab using the SRN module freely available from PDPtool Software (McClelland, 2015).

A Simulation (2; $\text{SRN}_{80:20}$ vs $\text{SRN}_{90:10}$) x Trial type (2; training vs. control) x Block (13; 1-13 blocks) mixed ANOVA analysed the acquisition and expression of sequence learning in the two SRN models across 13 training blocks. As shown in Figure 9, the index of performance (1-LCR) improved with practice selectively for the most likely successors, reflecting the higher activation of the target output relative to the remaining units, Trial type x Block, *F*(8.67, 850.03)[3] = 865.68, p<.001, η_p^2 =.90. Interestingly, the difference between high and low probability responses grew larger for $\text{SRN}_{90:10}$, reflecting the model's sensitivity to the difference in likelihood between training and control successors, Simulation x Trial type x Block, F(8.67, 850.03) = 34.59, p<.001, η_p^2 =.26.

We surmised that the reduction in learning observed in $\text{SRN}_{80:20}$ could make the CSE more difficult to achieve, or to delay its appearance. A Simulation (2; $\text{SRN}_{80:20}$ vs $\text{SRN}_{90:10}$) x Trial type (2; training vs. control) x Previous Trial type (2; training vs. control) mixed ANOVA compared the CSE in the two SRN models across blocks 9-13, when learning was most stable. As shown in Figure 10, the CSE obtained for $\text{SRN}_{90:10}$ did closely replicate the pattern reported by Beesley et al. (2012), and it reached a difference of 0.18 between the expression of learning after a training or after a control trial. In contrast, the output of $\text{SRN}_{80:20}$ showed that this effect was comparatively small, if not absent (0.02) after this amount of training, and even after using the optimal parameters of learning rate and number of hidden units, Simulation x Trial Type x Previous Trial Type, F(1,98) = 62.40, p<.001, η_p^2 =.39.

In sum, the results of the present simulation study suggest that, even though the SRN could be useful to account for the CSE observed when the training successors arose nine times more often than the control trials, the model is barely sensitive to the status of the previous trial when the structure is made as noisy as that used in the present set of experiments. Even though it is still possible to claim that a different model of associative learning could account for the CSE observed in this paradigm based on a more local representation of past trials, or even to attribute the observed effects to the residual level of sensitivity displayed by $\text{SRN}_{80:20}$ at the end of training, we believe that these results, together with the evidence of OSE provided by this study provide compelling evidence in favor of the control account.

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[3] Greenhouse-Geisser correction for violation of sphericity assumptions.

Therefore, throughout repeated experience with the sequence, participants learned to deal with the training series as congruent with their implicit expectations, and to respond to the appearance of punctual control trials as incongruent with them. The violation of expectancies induced by control trials presumably triggered a conflict response and subsequently increased the amount of cognitive control exerted on the following trial (Botvinick et al., 2001), which reduced the expression of ISL (i.e., CSE; Jiménez et al., 2009).

Conclusions

The main purpose of this work was to explore whether and how cognitive control may modulate the expression of implicit sequence learning. The outcomes of these experimental series demonstrate that when cognitive control mechanisms are called in (i.e., OSE, CSE), they reduce the expression of this learning.

In these studies, we highlighted for the first time the existence of an oddball-dependent sequence effect (OSE), in which sequence learning was modulated by a task- and sequence-irrelevant dimension, orthogonal to the learning process (unlike control trials). Crucially, this effect can be explained by the same cognitive control mechanisms engaged after conflict detection, but also by well-known behavioral and electrophysiological indices of attentional reallocation on task-relevant information after deviance distraction. In addition, we replicated (with higher power) the CSE as in Jiménez et al., (2009) in the context of a noisier SRT task, and showed that these effects are not easily accounted for an associative model such as the SRN. Thus, the results are most consistent with the interpretation that presenting a target in a position different from the one predicted by the training sequence triggered a conflict response and subsequent control, which decreased participants' reliance on the sequence.

In sum, these experiments show that the automatic and implicit expression of sequence learning can be flexibly controlled on a trial by trial basis, and contribute to improve the present understanding of how we can balance between our ability to exert effortful and goal-directed cognitive control, and the taking advantage of all possible forms of adaptive and automatic behavior.

References

Beesley, T., Jones, F. W., & Shanks, D. R. (2012). Out of control: An associative account of congruency effects in sequence learning. *Consciousness and Cognition*, *21*, 413–421. https://doi.org/10.1016/j.concog.2011.09.020

Berti, S. (2008). Cognitive control after distraction: Event-related brain potentials (ERPs) dissociate between different processes of attentional allocation. *Psychophysiology*, *45*(4), 608–620. https://doi.org/10.1111/j.1469-8986.2008.00660.x

Berti, S., Roeber, U., & Schröger, E. (2004). Bottom-Up Influences on Working Memory: Behavioral and Electrophysiological Distraction Varies with Distractor Strength. *Experimental Psychology*, *51*(4), 249–257.

Berti, S., & Schröger, E. (2001). A comparison of auditory and visual distraction effects: behavioral and event-related indices. *Cognitive Brain Research*, *10*(3), 265–273. https://doi.org/10.1016/S0926-6410(00)00044-6

Berti, S., & Schröger, E. (2003). Working memory controls involuntary attention switching: evidence from an auditory distraction paradigm. *European Journal of Neuroscience*, *17*, 1119–1122.

Berti, S., & Schröger, E. (2004). Distraction effects in vision: behavioral and event-related potential indices. *NeuroReport*, *15*(4), 665–669.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). *Conflict Monitoring and Cognitive Control*. *Psychological Review* (Vol. 108). Posner & Petersen. Retrieved from https://pdfs.semanticscholar.org/05b1/99fc0e63bc3a7975f91112b79fa0d21bd3161.pdf

Braem, S., Abrahamse, E. L., Duthoo, W., & Notebaert, W. (2014). What determines the specificity of conflict adaptation? A review, critical analysis, and proposed synthesis.

Frontiers in Psychology, *5*(1134), 1–13. https://doi.org/10.3389/fpsyg.2014.01134

Braem, S., Bugg, J. M., Schmidt, J. R., Crump, M. J. C., Weissman, D. H., Notebaert, W., & Egner, T. (2019). Measuring Adaptive Control in Conflict Tasks. *Trends in Cognitive Sciences*, *23*(9), 769–783. https://doi.org/10.1016/j.tics.2019.07.002

Braver, T. S. (2012). The variable nature of cognitive control: A dual-mechanisms framework. *Trends in Cognitive Sciences*, *16*(2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010

Callejas, A., Lupiàñez, J., Funes, M. J., & Tudela, P. (2005). Modulations among the alerting, orienting and executive control networks. *Experimental Brain Research*, *167*(1), 27–37. https://doi.org/10.1007/s00221-005-2365-z

Crump, M. J. C., Gong, Z., & Milliken, B. (2006). The context-specific proportion congruent Stroop effect: Location as a contextual cue. *Psychonomic Bulletin & Review*, *13*(2), 316–321. https://doi.org/10.3758/BF03193850

D'Angelo, M. C., Jiménez, L., Milliken, B., & Lupiáñez, J. (2013). On the specificity of sequential congruency effects in implicit learning of motor and perceptual sequences. *Journal of Experimental Psychology: Learning Memory and Cognition*, *39*(1), 69–84. https://doi.org/10.1037/a0028474

D'Angelo, M. C., Milliken, B., Jiménez, L., & Lupiáñez, J. (2013). Implementing flexibility in automaticity: Evidence from context-specific implicit sequence learning. *Consciousness and Cognition*, *22*(1), 64–81. https://doi.org/10.1016/j.concog.2012.11.002

Destrebecqz, A., & Cleeremans, A. (2001). Can sequence learning be implicit? New evidence with the propcess dissociation procedure. *Psychonomic Bulletin & Review*, *8*(2), 343–350.

Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014a). The

Congruency Sequence Effect 3.0: A Critical Test of Conflict Adaptation. *PLoS ONE*, *9*(10), e110462. https://doi.org/10.1371/journal.pone.0110462

Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014b). The heterogeneous world of congruency sequence effects: an update. *Frontiers in Psychology*, *5*(1001), 1–9. https://doi.org/10.3389/fpsyg.2014.01001

Elman, J. L. (1990). Finding structure in time. *Cognitive Science*, *14*, 179–211.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(4), 380–390.

Escera, C., Alho, K., Winkler, I., & Näätänen, R. (1998). Neural Mechanisms of Involuntary Attention to Acoustic Novelty and Change. *Journal of Cognitive Neuroscience*, *10*(5), 590–604.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*, 1149-1160.

Frensch, P. A., & Miner, C. S. (1994). Effects of presentation rate and individual differences in short-term memory capacity on an indirect measure of serial learning. *Memory & Cognition, 22*(1), 95-110.

JASP Team (2018). JASP (Version 0.9)[Computer software].

Jiménez, L., Mendez, C., & Cleeremans, A. (1996). Comparing direct and indirect measures of sequence learning. *Journal ofExperimental Psychology: Learning, Memory and Cognition, 22*, 948–969

Jiménez, L., Lupiáñez, J., & Vaquero, J. M. M. (2009). Sequential congruency effects in implicit sequence learning. *Consciousness and Cognition*, *18*(3), 690–700. https://doi.org/10.1016/j.concog.2009.04.006

Jiménez, L., Vaquero, J. M. M., & Lupiáñez, J. (2006). Qualitative differences between implicit and explicit sequence learning. *Journal of Experimental Psychology: Learning Memory and Cognition*, *32*(3), 475–490. https://doi.org/10.1037/0278-7393.32.3.475

Kimura, M., Schröger, E., & Czigler, I. (2011). Visual mismatch negativity and its importance in visual cognitive sciences. *NeuroReport*, *22*(14), 669–673. https://doi.org/10.1097/WNR.0b013e32834973ba

Kimura, M., Widmann, A., & Schröger, E. (2010). Human visual system automatically represents large-scale sequential regularities. *Brain Research*, *1317*, 165–179. https://doi.org/10.1016/j.brainres.2009.12.076

Knowlton, B. J., & Squire, L. R. (1996). Artificial grammar learning depends on implicit acquisition of both abstract and exemplar-specific information. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(1), 169–181. https://doi.org/10.1037/0278-7393.22.1.169

Leiva, A., Parmentier, F. B. R., Elchlepp, H., & Verbruggen, F. (2015). Reorienting the mind: The impact of novel sounds on go/no-go performance. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(5), 1197–1202. https://doi.org/10.1037/xhp0000111

McClelland, J.L. (2015, December 16). *Explorations in Parallel Distributed Processing: A Handbook of Models, Programs, and Exercises*. https://web.stanford.edu/group/pdplab/pdphandbook/handbook.pdf

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, *19*(1), 1–32. https://doi.org/10.1016/0010-0285(87)90002-8

Parmentier, F. B. R. (2008). Towards a cognitive model of distraction by auditory novelty: The role of involuntary attention capture and semantic processing. *Cognition*, *109*(3), 345–362. https://doi.org/10.1016/j.cognition.2008.09.005

Parmentier, F. B. R. (2014). The cognitive determinants of behavioral distraction by deviant auditory stimuli: a review. *Psychological Research*, *78*(3), 321–338. https://doi.org/10.1007/s00426-013-0534-4

Parmentier, F. B. R. (2016). Deviant Sounds Yield Distraction Irrespective of the Sounds' Informational Value. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(6), 837–846. https://doi.org/10.1037/xhp0000195

Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the Detection of Signals. *Journal of Experimental Psychology: General*, *109*(2), 160–174. Retrieved from https://psych.hanover.edu/classes/Cognition/papers/posner 1980.pdf

Ravden, D., & Polich, J. (1998). Habituation of P300 from visual stimuli. *International Journal of Psychophysiology*, *30*(3), 359–365. https://doi.org/10.1016/S0167-8760(98)00039-7

Reed, J., & Johnson, P. (1994). Assessing Implicit Learning With Indirect Tests: Determining What Is Learned About Sequence Structure. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*(3), 585–594. https://doi.org/10.1037/0278-7393.20.3.585

Rinne, T., Kirjavainen, S., Salonen, O., Degerman, A., Kang, X., Woods, D. L., *et al.* (2007). Distributed cortical networks for focused auditory attention and distraction. *Neuroscience Letters*, 416(3), 247–251. https://doi.org/10.1016/j.neulet.2007.01.077

Roeber, U., Berti, S., Widmann, A., & Schröger, E. (2005). Response repetition vs. alternation modulates behavioral and electrophysiological effects of distraction. *Cognitive Brain Research*, 22(3), 451–456. https://doi.org/10.1016/j.cogbrainres.2004.10.001

Rumelhart, D. E., & McClelland, J. L. (1986). *Parallel distributed processing: Explorations in the microstructure ofcognition (Vol. 1): Foundations*. Cambridge, MA: MIT Press.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science, 274*(5294), 1926–1928. https://doi.org/10.1126/science.274.5294.1926

Schvaneveldt, R. W., & Gomez, R. L. (1998). Attention and probabilistic sequence learning. *Psychological Research*, *61*(3), 175–190. https://doi.org/10.1007/s004260050023

Toh, Y. N., Remington, R. W., & Lee, V. G. (2021). Sequence learning is surprisingly fragile in visual search. *J Exp Psychol Hum Percept Perform*, *47*(10), 1378-1394. https://doi.org/10.1037/xhp0000952

Tipper, S.V. (1985). The Negative Priming Effect: Inhibitory Priming by Ignored Objects. *The Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *37A*(4), 571-590. https://doi.org/10.1080/14640748508400920

Van Gaal, S., Lamme, V. A. F., & Ridderinkhof, K. R. (2010). Unconsciously Triggered Conflict Adaptation. *PLoS ONE*, *5*(7), 11508. https://doi.org/10.1371/journal.pone.0011508

Vaquero, J. M. M., Lupiáñez, J., & Jiménez, L. (2019). Asymmetrical effects of control on the expression of implicit sequence learning. *Psychological Research*, *1*, 1–15. https://doi.org/10.1007/s00426-019-01222-1

Winkler, I. (2007). Interpreting the Mismatch Negativity. *Journal of Psychophysiology*, *21*(3–4), 147–163. https://doi.org/10.1027/0269-8803.21.34.147