

# Mechanisms of spatial contextual cueing in younger and older adults

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## Abstract

The contextual cueing effect is the phenomenon observed when response time (RT) becomes faster in visual search in repeated context compared with a new one. In the present study, we explored whether the mechanisms involved in the effect are age dependent. We investigated it in younger ( $N=20$ , 12 women,  $21.2 \pm 1.75$  years) and older ( $N=19$ , nine women,  $67.05 \pm 3.94$  years) adults. We found a faster target identification in the repeated configurations with similar magnitude in the two age groups, which indicates that this contextual cueing effect remained intact even in the older participants. To shed light on the underlying mechanisms, we measured and compared the amplitude of three event-related potentials: N2pc, P3, and response-locked LRP. In the younger group, the larger contextual cueing effect (novel-minus-repeated RT difference) correlated positively with a larger difference in amplitude for repeated compared with novel configurations for both the N2pc and the P3 components, but there was no correlation with the response-locked lateralized readiness potential (rLRP) amplitude difference. However, in the older group, only the rLRP amplitude difference between novel and repeated configurations showed an enhancement with larger contextual cueing. These results suggest that different mechanisms are responsible for the contextual effect in the two age groups. It has both an early and an intermediate locus in younger adults: effective attentional allocation and successful stimulus categorization, or decision-making confidence are involved; while in older adults, a late locus was identified: a more efficient response organization led to a faster reaction.

## KEYWORDS

aging, contextual cueing, ERP, LRP, N2pc, P3

## 1 | INTRODUCTION

When looking to buy for our favorite chocolate bar in the store, we can easily spot it on the shelf if it is among the usual products, even if we have not been to that store

before. However, if they just rearranged the store we regularly go to and put our chocolate bar among other types of products, it will take longer to find it. This phenomenon of our previous experience guiding our attention to specific locations can be studied in the laboratory by using the

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contextual cueing paradigm (Chun & Jiang, 1998). In the most studied version of the paradigm, participants have to find the target letter “T” among distractor letter “L”-s and respond to the orientation (left/right) of the target by pressing a button. The arrangement of the distractor letters serves as a context, which is repeated in half of the trials (repeated configurations), while in the remaining trials, the spatial layout of the distractors is varied (novel configurations). Contextual cueing is defined as shorter reaction times (RTs) and increased response accuracy for repeated compared with novel configurations during the visual search task.

The locus of this phenomenon is still a matter of debate (Sisk et al., 2019). The most widely accepted explanation is the attentional guidance account, according to which the context directs attention to the appropriate focal point in the space in the visual search task, that is, the search process becomes faster even before the target stimulus is found by the individual (early locus). This idea is supported by many studies, for example, Chun and Jiang (1998) found that context repetition caused a reduced search slope (indexing the time necessary to search items in the configuration), but no change in intercept (the time necessary for all other processes) when the reaction time (RT) of target detection was measured as a function of set size. In another study (Jiang & Chun, 2001), when selective attention was manipulated by using contexts in to-be-attended and to-be-ignored colors, only contexts in to-be-attended colors facilitated the visual search. Eye-tracking studies also support the idea of improved attentional guidance (e.g., Harris & Remington, 2017; Manginelli & Pollmann, 2009). Other researchers, on the contrary, claim that this theory alone does not explain the contextual cueing effect, since it also exists in cases where all the information about the position of the target stimulus is available in advance, and it disappears if there is interference at the level of response selection. According to these researchers, the contextual cueing effect can be explained, to a greater extent, by the response facilitation account (late locus), that is, the context accelerates response-related processes in a later phase (e.g., Kunar et al., 2007). This may mean that the target verification or the response selection threshold is reduced, that is, the threshold will be crossed sooner, leading to a faster reaction.

Studying this question in older adults may help to elaborate on the importance of the early and late locus of the contextual cueing effect in younger adults through uncovering mechanisms that have not been targeted or expose aspects that were not easily distinguishable in studies with younger adults. Many cognitive processes undergo change with aging (e.g., Cabeza, 2002; Craik & Byrd, 1982; Davis et al., 2008; Reuter-Lorenz & Park, 2014; Salthouse, 1996); thus, the question arises whether the same processes are

affected in the younger and older age groups, or the altered cognitive processes lead to utilizing a different mechanism in older adults. It is also possible that older people do not show contextual cueing effect at all. So far, the results have been contradictory regarding the latter question: Some studies found an intact contextual cueing effect (Howard et al., 2004; Lyon et al., 2014), while others observed an age-related impairment (Smyth & Shanks, 2011), although Preuschhof et al. (2019) claimed that the reason for this is the slower emergence of the effect, with the older participants needing more repetitions than the young adults for an observable contextual cueing effect.

Studies tend to focus most of the time on which cognitive functions are impaired in older adults, and how. However, this does not apply to all cognitive functions, and some could even be used to compensate for impaired functions. A good candidate might be implicit learning, which we believe does not show any deterioration with aging (although there are results to the contrary, for example, Rieckmann & Bäckman, 2009; Ward & Shanks, 2018), as well as contextual cueing is a form of implicit learning. Characteristically in this process, participants learn the associations between target locations and spatial configurations without any explicit instructions or knowledge of this association; thus, the learning is unintentional, but also underlied by a robust and high-capacity mechanism. If contextual cueing is proven to be preserved with aging, then it might be used as a tool in compensating for the limited-capacity, goal-driven form of attention.

Further insight into what processes drive the spatial contextual cueing effect and how those processes may change with age can be gained by measuring the event-related potential (ERP) components. To disentangle attention-related and response-related processes, earlier ERP studies investigated the following components: the N2pc; a centro-parietal positivity, the P3; the stimulus-locked lateralized readiness potential (sLRP); and the response-locked lateralized readiness potential (rLRP).

The N2pc component is a negative deflection of the ERP at parieto-occipital sites contralateral to the visual field in which the stimulus appears. It is observed in the 200–400 ms poststimulus time window and is calculated as the difference in the potentials elicited by the stimulus contralaterally and ipsilaterally to the visual field in which the stimulus is presented (contralateral-minus-ipsilateral difference potential). The N2pc has been associated with different aspects of attentional selection and has been used to track the deployment of attention in visual space. One possibility is that it reflects allocation of attentional resources to the target (attentional allocation assumption), which assumption forms the basis for the studies of N2pc in the case of the spatial contextual cueing effect (Johnson et al., 2007; Schankin et al., 2011; Schankin &

Schubö, 2009, 2010; Zinchenko et al., 2020). In the spatial contextual cueing paradigm, it is the repeated spatial configurations (i.e., the repeated target and distractors together) that cue the location of the target leading to more efficient shift of attention. Another possibility is that N2pc corresponds to suppression of the surrounding distractors (attentional selection assumption, Luck & Hillyard, 1994), and effective filtering is expressed in enhanced amplitude and longer latency of the N2pc when task difficulty increases (Luck & Hillyard, 1990). In the context of spatial cueing, this has been supported by Woodman et al.'s (2009) study where N2pc amplitude was modified depending on whether the distractors (to be suppressed) were displayed beforehand or not, that is, whether preliminary processing of task-relevant features had already taken place before the target appeared. Furthermore, in Kiss et al.'s (2008) experiments the amplitude did not reflect the shift of spatial attention, but rather selective attentional processes after attention was shifted. These studies, however, differ from the spatial contextual cueing paradigm on one essential point: Here, the spatial configuration of the distractors is the cue. In other words, it is very likely that attentional allocation will take place when the configuration appears, and familiar, informative cues could make it more efficient. Attentional selection (distractor suppression) could still be a viable explanation. In this case, the stimuli configurations in the repeated contexts could be learned and the distractors would be more efficiently suppressed (note that this possibility is still likely based on spatial information). Here, instead of providing additional information, the distractors interfere with the task. According to both accounts, the spatial contextual cueing effect will be expressed as a larger amplitude for repeated compared with novel configurations.

The results so far tend to support a spatial contextual cueing effect in the component, although it is less straightforward which account provides a better explanation. Studies using the spatial contextual cueing paradigm tend to favor the attentional allocation explanation. Johnson et al. (2007) found an enhanced N2pc for repeated compared with novel configurations in the 200–300 ms post-stimulus time window at temporo-parieto-occipital electrode sites. In a later study by Schankin and Schubö (2009), a larger N2pc was observed for repeated compared with novel configurations in the 270–330 ms poststimulus time window at the PO7/PO8 electrode sites, but this increase did not reach significance. However, the same study found a correlation between the behavioral contextual cueing effect (the novel-minus-repeated RT difference) and the difference in amplitude between the two conditions: with the larger behavioral RT difference also being paired with a larger amplitude difference. Both studies interpreted the results as supporting

the attentional allocation assumption. In their follow-up study, Schankin and Schubö (2010) included a condition in which the location of the target was cued before presenting the configuration; with the result that the amplitude of the N2pc for repeated configurations was larger than that for novel configurations in both the cued and uncued conditions. This questions the attentional allocation explanation, as in the cued condition it has already supposedly happened; and favors the attentional selection explanation, that is, the increased amplitude in the N2pc component indicates that distinguishing the target from the distractors was easier in the repeated (familiar) context (Schankin & Schubö, 2010). In both studies by Schankin and Schubö (2009, 2010), the targets were in the same locations in the repeated and in the novel configurations; thus, enhanced processing of target location is an unlikely explanation for the difference in N2pc. A recent study by Zinchenko et al. (2020) also found an enhanced N2pc for repeated compared with novel configurations, and further showed that an earlier lateralized posterior component, the N1pc which reflects an orienting response to salient stimuli, influences the N2pc. Learned location became salient over time and that initial learning persisted even after reallocating the target. The authors interpreted the result within the attentional allocation explanation. In the present study, we expected to find a larger N2pc amplitude for repeated compared with novel configurations. We also examined the relationship between the behavioral and the N2pc amplitude contextual cueing effects to see whether the correlation from Schankin and Schubö (2009) could be replicated.

All results cited above were obtained with younger adults. In older adults, the N2pc component is delayed and attenuated in visual search tasks (Amenedo et al., 2012; Lorenzo-López et al., 2008), although it is possible that the underlying processes may be made more efficient with training (O'Brien et al., 2013, 2015). Thus, we anticipated a smaller N2pc in the older adults. More importantly, a contextual cueing effect could still be observed as a difference in amplitude if the attention-related processes continue to play a role. Besides our main aim of determining whether early or late processes contribute to the contextual cueing effect in different age groups, some additional tentative predictions could be made regarding the two accounts for N2pc. For older adults, inhibiting visual distractors is more difficult compared with younger adults (Gaál et al., 2020; Kojouharova et al., 2020). Because of that, in the spatial contextual cueing paradigm, they may process more information about the spatial configurations, and then use this additional information to improve performance on the task for the repeated configurations resulting in a larger contextual cueing effect. Within the attentional allocation assumption, more spatial information leads to more

efficient shift of attention and a larger N2pc for repeated compared with novel configurations than in the younger adults. This possibility assumes an intact attentional allocation mechanism. Alternatively, within the attentional selection assumption, although the contextual cueing effect (implicit learning of spatial configurations) may be preserved, as a consequence of impaired distractor suppression, the N2pc component may disappear. Thus, while our experiment was not designed to distinguish between the two assumptions, including a different age group may help shed some light on the underlying mechanisms of the N2pc component.

In the few available studies, a consistent result regarding the effect of context on the ERP is a larger positivity for repeated compared with novel configurations over central and parietal electrode sites in the 400–700 ms (Schankin & Schubö, 2009); the 470–530 ms (Schankin & Schubö, 2010); and the 500–600 ms (Schankin et al., 2011) time windows. In these studies, they term this component as P3 (Schankin & Schubö, 2009, 2010) or late positivity (Schankin et al., 2011). The effect seems to be specific to conditions without additional manipulations (e.g., uncued trials, Schankin & Schubö, 2010; target-present trials, Schankin et al., 2011), and to be more pronounced for participants that showed a behavioral spatial contextual cueing effect (Schankin et al., 2011). Additionally, in the latter study the behavioral contextual cueing effect and the difference in amplitude between novel and repeated configurations correlated: the larger the spatial contextual cueing effect, the larger the difference in amplitude between the configurations. In these mentioned studies, the component was interpreted as a correlate of response-related processes more generally, and as adjusted response threshold more specifically, that is, a more liberal response threshold in the case of repeated context. However, there is no consensus about what cognitive processes P3 indicates, or whether it reflects psychological processes at all (Verleger, 1988, 2020). In the current experiment, we assumed that the P3 component shows an intermediate process between attention and response, which can be a correlate of target recognition (Chao et al., 1995; Squires et al., 1973; Verleger, 1988) and decision (Kelly & O'Connell, 2015; O'Connell et al., 2012; Twomey et al., 2015), larger amplitude indicating better predictability, and greater decision confidence (Eimer & Mazza, 2005; Hillyard et al., 1971; Parasuraman et al., 1982; Squires et al., 1973, 1975). We expected to replicate the results in the younger adult group. Regarding the older adults, as this component is likely a part of the P3 complex, it was expected to be attenuated overall compared with the younger adults over parietal locations (e.g., Li et al., 2013; Lorenzo-López et al., 2008; O'Connell et al., 2012; Pfefferbaum & Ford, 1988; Polich, 1997). A

difference in amplitude between the repeated and the novel configurations will indicate a locus of the contextual cueing effect.

The response-related processes are specifically reflected by the lateralized readiness potential (LRP), which is measured over the motor cortex and is observed contralaterally to the hand used to respond to a target (calculated as the contralateral-minus-ipsilateral difference potential, often at the C3/C4 electrode sites). When measured relative to the stimulus presentation (sLRP), it reflects response selection while when measured relative to response (rLRP), it indicates response preparation and/or execution (Schankin & Schubö, 2009, 2010). Both stimulus- and response-locked components might be correlates of processes that are enhanced by repeated context. Earlier studies examining this obtained somewhat equivocal results. Schankin and Schubö (2009) found only a correlation between the time from onset to response in rLRP and the behavioral spatial contextual cueing effect, with the time being shorter (less time needed for response preparation and execution) when the behavioral effect was larger. In Schankin and Schubö (2010), there was no effect of context for rLRP; however, the sLRP onset latency was earlier only for cued trials. Nevertheless, their contribution to the spatial contextual cueing effect cannot yet be entirely excluded in younger adults. The components could be especially relevant in the case of older adults, who generally are less efficient in suppressing irrelevant responses (e.g., Vallesi & Stuss, 2010; Wild-Wall & Falkenstein, 2010; Yordanova, 2004). In other paradigms, the LRP amplitude has been shown to be larger in older compared with younger adults (Cespón et al., 2013; Roggeveen et al., 2007; Wild-Wall et al., 2008; Yordanova, 2004), which increase may stem from worse inhibitory control (Roggeveen et al., 2007) or increased response threshold (Wild-Wall et al., 2008; Yordanova, 2004). All in all, it is possible that repeated (familiar) context will not only help response selection, but also response preparation and execution, which can be reflected in LRP amplitude changes.

In summary, our goal was to replicate earlier results of the Chun and Jiang (1998) study, that is, younger participants identify the target faster and more accurately in repeated rather than novel configurations in the contextual cueing task. Although earlier results are controversial, we hypothesized that the contextual cueing effect would be intact also in an older age group. To explore the mechanism of the contextual cueing effect, we observed the changes of N2pc and s/rLRP components, showing whether early (attentional guidance) or late (response facilitation) locus is involved: enhanced N2pc amplitude in repeated versus novel configurations would reflect allocation of visual-spatial attention, while changes in LRP amplitude could indicate more effective response execution



(decreased amplitude) in the repeated configurations. Changes in the P3 component would indicate whether other, intermediate processes such as target recognition or stimulus categorization also play a role. And finally, age-group differences could show whether the same processes are involved in contextual cueing for both younger and older adults.

## 2 | METHOD

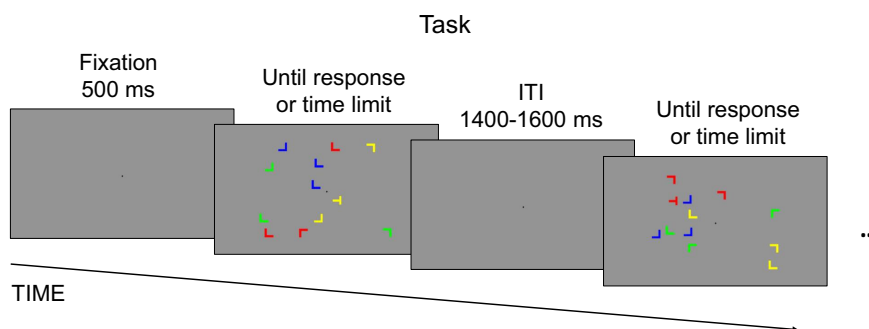
### 2.1 | Participants

Twenty younger and 20 older adults participated in the experiment. We used G\*Power 3.9.1.6 to determine the sample size (Faul et al., 2007). The calculations were based on a repeated-measures ANOVA design with CONFIGURATION (repeated, novel) as a within-subject factor and GROUP (younger, older) as a between-subject factor (for more details see Data Analysis in Methods). To detect a moderate effect size ( $\eta_p^2=0.06$ ) for a main effect of CONFIGURATION and a CONFIGURATION  $\times$  GROUP interaction at 80% power and .05 alpha, a total sample of 34 participants is required (i.e., 17 participants per group). For more details see the [Supplementary Material](#). The younger adults were recruited through a school cooperative, and the older adults were recruited from our own database. All participants received payment for their participation. One participant from the older group was excluded from the analyses, because noisy EEG data resulted in no epochs in one of the blocks. Thus, the final sample consisted of 20 participants in the younger group (12 women,  $M=21.2$  years,  $SD=1.75$ , 2 left-handed) and 19 participants in the older group (nine women,  $M=67.05$  years,  $SD=3.94$ , all right-handed). All had normal or corrected-to-normal vision and no

reported neurological or psychiatric disorders. To exclude dementia-related differences between the age groups, we measured intelligence with four subtests of the Hungarian version of Wechsler Adult Intelligence Scale (WAIS-IV, Rózsa et al., 2010) representing the four major components: Similarities—verbal comprehension; Digit Span—working memory; Matrix Reasoning—perceptual reasoning; and Coding—processing speed. The scaled scores (where the age-group average is 10) achieved by the younger group were as follows: Similarities:  $M=10.75$  ( $SD=3.32$ ); Digit span:  $M=10.4$  ( $SD=2.13$ ); Matrix Reasoning:  $M=10.9$  ( $SD=2.14$ ); and Coding:  $M=11.39$  ( $SD=2.19$ ). The older group achieved the following scores on the four subtests: Similarities:  $M=12.47$  ( $SD=1.9$ ); Digit Span:  $M=10.74$  ( $SD=2.15$ ); matrix reasoning:  $M=13.21$  ( $SD=3.82$ ); and Coding:  $M=13.21$  ( $SD=2.38$ ). Written informed consent was obtained from all individual participants included in the study.

### 2.2 | Stimuli and procedure

The stimuli were presented on a 24" monitor (BenQ, resolution 1920  $\times$  1080, refresh rate 60Hz) located at a viewing distance of 140 cm. The stimuli were configurations consisting of 12 items placed randomly in an invisible 8  $\times$  6 grid (48 positions) with examples presented in [Figure 1](#). The size of the grid was 560  $\times$  420 px (subtending 6.32  $\times$  4.77 degrees of visual angle). The 12 items were one "T" (target) and 11 "L"-s (distractors). Each item was 36  $\times$  36 px (0.41°  $\times$  0.41°), and its placement in a grid cell was jittered anywhere between 0 and 12 px (in 3 px steps) from the center of the cell. The "T" (target) item could only be rotated 90° to the left or right; while each "L" (distractor) item could be rotated with the following orientations: 0°, 90°, 180°, or 270°. Of the 12 items on the



**FIGURE 1** Experimental design of the contextual cueing paradigm. One display consisted of a spatial configuration of 12 items—one target (letter "T") and 11 distractor items (the letter "L"). Participants had to respond by pressing the left/right key on a keyboard depending on whether the target letter "T" was rotated to the left/right. The configuration was presented until a response or for no longer than 2000 ms in the younger group, and 4000 ms in the older group. The intertrial interval (ITI) was 1400–1600 ms. Twelve displays were repeated 30 times during the experiment, while the other configurations were not repeated. The target's orientation varied randomly in each display.

grid, four were blue (RGB: 0, 0, 255), four were red (RGB: 255, 0, 0), four were green (RGB: 0, 255, 0), and four were yellow (RGB: 0, 255, 255) with the background color being gray (RGB: 127, 127, 127).

The configurations were presented in sequences of 24 trials. Each trial contained one configuration, and there were 12 repeated and 12 novel configurations within a sequence. The 12 repeated configurations differed from each other but remained the same throughout the experiment: the placement, color, and rotation of the distractor items as well as the placement and color of the target item were fixed. The rotation of the target item was the only parameter that varied (i.e., in the same configuration the “T” target was sometimes rotated to the left and sometimes to the right). The exact same placement of the target item was applied for the 12 novel configurations within a sequence mirroring the repeated configurations, but all other parameters of the target and the distractor items were varied randomly. Each novel configuration was presented only once during the session (for each participant, but not exclusively), and all novel configurations were different from the repeated configurations. Each participant was randomly assigned repeated and novel configurations. The target item appeared an equal number of times in each of the quadrants, and its rotation was counterbalanced within a sequence. The only additional constraint regarding the positions of the items was that there were no more than four items in each quadrant, otherwise the positions were chosen randomly. Both the constraint and the randomization resulted in the following possible distributions of the stimuli: eight stimuli to the left and four stimuli to the right (~20% overall), six stimuli to the left and six stimuli to the right (~60% overall), and four stimuli to the left and eight stimuli to the right (~20% overall) of the fixation point, with an overall average of six stimuli to the right and six stimuli to the left of the fixation point. The experiment started with 24 practice trials for which the configurations were randomly generated and did not appear again during the experimental part. The trials were randomized within a sequence. There were 30 sequences, with a total of 360 repeated (the same 12 configurations 30 times) and 360 novel configurations.

A sequence (shown in [Figure 1](#)) started with a fixation point (a black circle 6×6 px, 0.07° of visual angle) being presented for 500ms in the center of the screen; then, the configuration appeared and remained on the screen until a response, or until a time limit was reached: 2000ms for the younger group and 4000ms for the older group. The different time limits for the two age groups were established in pilot experiments. The time limits allowed sufficient time to find the target in both groups, and the longer time limit in the older group ensured that their error rate was comparable to that of the younger group, that is, task difficulty

was similar for both groups.<sup>1</sup> The participants were instructed to reply as fast and as accurately as possible. On a modified keyboard with only two keys, the participants responded with their left hand by pressing the “A” key if the target item was rotated to the left; and the “L” key with their right hand, if it was rotated to the right. The participants did not see the markings on the keys; they were only told to press the left or the right key. An intertrial interval (ITI) of 1400; 1450; 1500; 1550; or 1600 ms was applied before the next trial began. The fixation point was visible throughout the sequence. After each sequence, the participant was given feedback about their percentage of correct responses and their RT, and they could then resume the experiment by pressing the Space bar on the keyboard.

The stimuli presentation and response recording were realized using the Cogent 2000 (Cogent 2000 Team, 2003) and Cogent Graphics (Romaya, 2008) toolboxes in MATLAB (MathWorks, Inc., 2015).

## 2.3 | Recording and measuring of the electrophysiological activity

Brain electric activity was recorded (bandwidth: DC-70 Hz; sampling rate 1000 Hz; BrainVision actiCHamp amplifier, BrainVision Recorder, BrainVision Products GMBH) with Ag/AgCl active electrodes placed at 27 locations (F7, F3, FC3, Fz, F4, F8, FC4, T7, C3, Cz, CP5, C4, T8, CP6, P8, P7, P3, Pz, P4, PO7, PO3, POz, O1, Oz, O2, PO4, and PO8) according to the extended 10–20 system using an elastic electrode cap (EasyCap, Brain Products GmbH). The reference electrode was placed on the nose. Eye movements were recorded with four electrodes placed around the eyes. Horizontal EOG was recorded with a bipolar configuration between electrodes positioned lateral to the outer canthi of the eyes (one electrode on each side). Vertical eye movement was monitored with a bipolar montage between two electrodes, one placed above and one below the left eye. The impedance of all electrodes was kept below 30 kΩ.

## 2.4 | Data analysis

### 2.4.1 | Behavioral analysis

To investigate how the behavioral responses change between conditions as the task progresses, the trials were

<sup>1</sup>While accommodating older adults for longer reaction times is a widespread practice in aging studies to ensure similar task difficulty, it is possible that it introduced a different confound as older adults had more time to explore the display. This will be addressed when discussing the results.

divided into six blocks. Each block consisted of five sequences (as described in Section 2), and thus contained 60 novel and 60 repeated configurations. Mean error rates and RT were analyzed. The data were averaged for each block and entered into a repeated-measures ANOVA with the BLOCK (6 blocks) and CONFIGURATION (repeated, novel) as the within-subject factors, and GROUP (younger, older) as the between-subject factor. All trials in which the response was faster than 150 ms were removed from analysis (four trials in total in the younger group and none in the older group). For the error rate, the percentage of wrong responses and the percentage of misses out of all trials were analyzed separately. For RT, only correct responses were analyzed.

Additionally, to better showcase the spatial contextual cueing effect, the novel-minus-repeated configuration RT differences were calculated for each participant and each block, and the data were entered into a repeated-measures ANOVA with the BLOCK (6 blocks) as the within-subject factors and GROUP (younger, older) as the between-subject factor.

## 2.4.2 | ERP analysis

The EEG signal was band-pass-filtered offline with a noncausal Kaiser-windowed FIR filter (lowpass filter parameters: cutoff frequency of 30 Hz, beta of 12.2653, a transition band of 10 Hz; highpass filter parameters: cutoff frequency of 0.1 Hz, beta of 5.6533, a transition band of 0.2 Hz). We ran an independent component analysis (ICA) to remove components related to eye movements. A separate analysis to account for eye movements can be found in the [Supplementary material](#). To investigate the N2pc and P3 components, stimulus-locked epochs were extracted for each event with a duration of 1100 ms, including a 100 ms prestimulus interval. To investigate the sLRP, stimulus-locked epochs with a duration of 2100 ms, including a 100 ms prestimulus interval, were extracted for each event. In the case of stimulus-locked epochs, the mean voltage during the 100 ms prestimulus interval served as the baseline for amplitude measurements. To investigate the rLRP, epochs locked to the responses from  $-400$  to  $200$  ms (duration of 600 ms) in the younger group and from  $-600$  to  $200$  ms (duration of 800 ms) in the older group were extracted. Here, the mean voltage during the  $-400$  to  $-300$  ms prerespone interval in the younger group and the  $-600$  to  $-500$  ms prerespone interval in the older group served as the baseline for amplitude measurements. Stimulus onset was measured by a photodiode, providing exact zero value for averaging. Epochs with an amplitude change exceeding  $100 \mu\text{V}$  on any channel were excluded from further analysis.

EEG data were preprocessed with MATLAB R2015a (MathWorks, Inc., 2015) and EEGLAB 2020.0 (Delorme & Makeig, 2004). ICA was performed with the runica function of the ERPLAB toolbox (Lopez-Calderon & Luck, 2014).

Because the spatial contextual cueing effect was already observable in the second block in the behavioral data, we collapsed the epochs across the last five blocks to analyze the differences between novel and repeated configurations after contextual learning (i.e., Blocks 2 through 6). In all cases, only epochs for trials with correct responses were included in the averages. The average number of epochs for each analysis can be found in the [Supplementary Material](#).

### *Comparing mean amplitudes*

We analyzed mean amplitudes. The time windows for calculating mean amplitude were chosen based on the grand averages separately for each group. They were centered around the maximum or minimum amplitude observed in the grand average and their length depended on the length of the observed component. In all cases, the chosen time windows conformed to values reported in the literature. The chosen electrode sites conform to sites previously studied in the literature. N2pc was studied over PO7/P8 and both LRP components were studied over C3/C4 in Schankin and Schubö (2009), Schankin and Schubö (2010), and Schankin et al. (2011). P3 is usually studied over midline central and parietal electrodes, and the scalp distribution in the present study suggested a more parietal distribution in both age groups; thus, the Pz electrode site was chosen for the analysis.

For the N2pc component, the epochs measured at the PO7 and PO8 electrode sites were averaged separately for trials in which the target appeared in the left visual field and for trials in which the target appeared in the right visual field; and separately for novel and repeated configurations. For trials in which the target was on the left, ERPs measured at PO7 were subtracted from ERPs measured at PO8 (contra-minus-ipsilateral difference to the presentation side of the target stimulus). For trials with a target on the right side, ERPs measured at PO8 were subtracted from ERPs measured at PO7. Because the stimuli were not equally distributed in the left and in the right visual field in all trials, it was possible that on those trials attention was guided in a bottom-up manner to the side with more stimuli. In this analysis, we included only trials in which there was an equal number of stimuli on either side of the fixation point. (An analysis containing all trials is available in the [Supplementary Material](#).) Mean amplitudes were defined as the mean amplitude for the 250–350 ms time window in the younger group and 330–430 ms time window in the older group.

For the P3 component, the EPRs at the Pz electrode site were calculated by averaging separately the epochs for repeated and novel configurations. Mean amplitudes were defined as the mean amplitude for the 400–600 ms time window for both groups.

For the sLRP and rLRP, the epochs at C3 and C4 electrode sites were averaged separately for responses with the left or with the right hand, and again, separately for novel and repeated configurations. For both sLRP and rLRP, differences for contra-minus-ipsilateral to the responding hand were calculated for electrodes C3 and C4 (e.g., ERPs measured and C3 were subtracted from ERPs measured at C4 for responses with the left hand). Mean amplitudes for sLRP were defined as the mean amplitude in the 600–1600 ms time window in both groups. Investigating the rLRP, mean amplitudes were defined as the mean of the prereponse time window from -150 to -50 ms in both groups.

For all components, the mean amplitudes were compared with repeated-measures ANOVA with a within-subject factor CONFIGURATION (repeated, novel) and a between-subject factor GROUP (younger, older). When appropriate, the Greenhouse–Geisser correction ( $\epsilon$ ) was applied. Effect size was calculated as partial eta square ( $\eta_p^2$ ). Bonferroni correction was applied in the case of post hoc tests.

### Relationship between the behavioral and the ERP spatial contextual cueing effects

Following the analyses in Schankin and Schubö's (2009) study, we also analyzed the relationship between the spatial contextual cueing effect observed in RT with the same effect in electrophysiological measures. To that end, we calculated the difference between novel and repeated (novel-minus-repeated) configurations for mean amplitude, and correlated that difference with the novel-minus-repeated configuration difference in RT (averaged across Blocks 2–6), separately in the older and in the younger group.

All statistical analyses were performed with JASP (JASP Team, 2023).

## 3 | RESULTS

### 3.1 | Behavioral results

The behavioral results are summarized in Table 1 and in Figure 2 (error rates) and Figure 3 (RT).

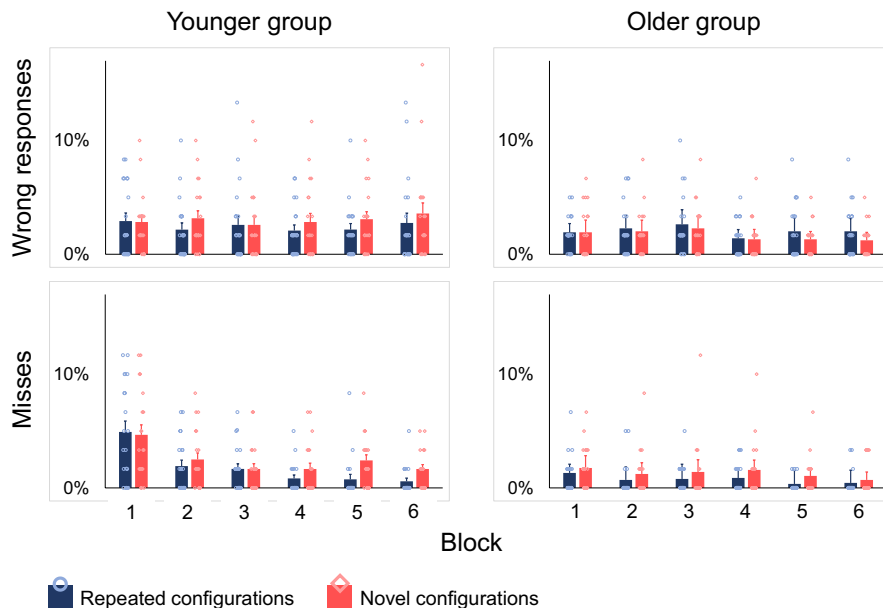
The analysis of error rate for wrong responses showed a significant interaction between GROUP and CONFIGURATION,  $F(1,37)=9.378$ ,  $p=.004$ ,  $\epsilon=0.808$ ,  $\eta_p^2=0.202$ . Post hoc tests, however, did not reach

**TABLE 1** Mean error rates (wrong responses and misses), reaction times, and the novel-minus-repeated reaction time differences (SEs in parenthesis) in the younger and older age groups for the novel and repeated displays in the six blocks.

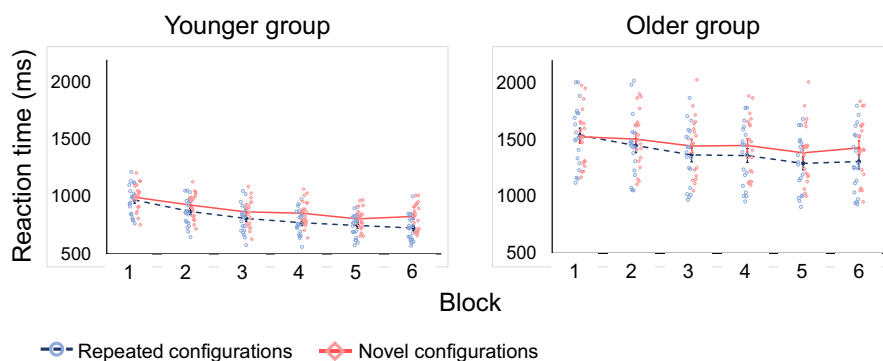
	Group	Configuration	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Error rate—wrong responses	Younger	Repeated	0.029 (0.007)	0.021 (0.006)	0.026 (0.008)	0.021 (0.005)	0.022 (0.005)	0.028 (0.009)
		Novel	0.028 (0.006)	0.032 (0.007)	0.026 (0.006)	0.028 (0.008)	0.031 (0.007)	0.036 (0.009)
Error rate—misses	Older	Repeated	0.019 (0.004)	0.023 (0.005)	0.026 (0.006)	0.014 (0.004)	0.02 (0.006)	0.02 (0.005)
		Novel	0.019 (0.005)	0.02 (0.005)	0.023 (0.005)	0.013 (0.004)	0.013 (0.003)	0.012 (0.003)
Reaction time	Younger	Repeated	0.049 (0.01)	0.019 (0.005)	0.017 (0.005)	0.008 (0.003)	0.008 (0.024)	0.006 (0.003)
		Novel	0.047 (0.009)	0.025 (0.006)	0.017 (0.005)	0.017 (0.005)	0.024 (0.005)	0.017 (0.004)
Cueing effect	Older	Repeated	0.013 (0.004)	0.007 (0.004)	0.008 (0.003)	0.009 (0.003)	0.004 (0.002)	0.004 (0.003)
		Novel	0.018 (0.005)	0.012 (0.005)	0.014 (0.006)	0.016 (0.006)	0.011 (0.004)	0.007 (0.003)
Reaction time	Younger	Repeated	972.1 (29.4)	870.6 (27.2)	810.4 (28.6)	772.2 (24.7)	748.6 (22.6)	726.1 (25.3)
		Novel	995.8 (26.0)	927.5 (24.7)	867.3 (26.4)	856.4 (25.2)	806.6 (21.3)	827.7 (26.5)
Cueing effect	Older	Repeated	1538.9 (63.7)	1448.1 (62.5)	1365.9 (60.6)	1360.5 (61.5)	1291.5 (56.6)	1307.6 (64.5)
		Novel	1526.4 (57.8)	1505.3 (57.7)	1444.4 (60.8)	1449.6 (58.7)	1384.3 (63.0)	1427.9 (62.4)
Cueing effect	Younger	Novel-minus-repeated RT	23.71 (11.68)	56.88 (14.29)	56.92 (8.82)	84.21 (12.97)	57.99 (11.31)	101.61 (11.68)
	Older		-12.52 (17.99)	57.21 (29.11)	78.45 (27.19)	89.13 (28.71)	92.78 (19.95)	120.28 (22.4)



**FIGURE 2** Mean error rates (on top: wrong responses, below: misses) in the younger (left) and in the older (right) groups for each block of the experiment. The blue color indicates the repeated configurations, and the red color indicates the novel configurations. Error bars show the standard errors, while the dots show the individual data.



**FIGURE 3** Mean reaction times (on top) in the younger (left) and in the older (right) groups for each block of the experiment. The blue color indicates the repeated configurations, and the red color indicates the novel configurations. Below this, cueing effect (novel-minus-repeated configurations RT differences) where the light green continuous line shows the results for the younger group and the dark green dashed line shows the results for the older group. Error bars show the standard errors, while the dots show the individual data.



significance, although in the younger group, there was a tendency for fewer wrong responses for repeated compared with novel configurations ( $p = .067$ ). All other main effects and interactions were not significant.

The comparison of error rate for misses showed a BLOCK main effect,  $F(5,185) = 13.532$ ,  $p < .001$ ,  $\epsilon = 0.571$ ,  $\eta_p^2 = 0.268$ . Post hoc tests showed that there were more misses in Block 1 compared with the rest (all  $ps < .001$ ), but no other differences. There were also CONFIGURATION,  $F(1,37) = 10.678$ ,  $p = .002$ ,  $\eta_p^2 = 0.224$ , and GROUP main effects,  $F(1,37) = 6.612$ ,  $p = .014$ ,  $\eta_p^2 = 0.152$ . There were more misses for novel

compared with repeated configurations and more misses in the younger than in the older group. A significant interaction between BLOCK and GROUP,  $F(5,185) = 6.448$ ,  $p < .001$ ,  $\epsilon = 0.621$ ,  $\eta_p^2 = 0.148$  and the following post hoc tests showed that the difference between groups was only in Block 1 ( $p < .001$ ), and the difference between Block 1 and the rest of the blocks was observable only in the younger group, all  $ps < .001$ . The remaining interactions were not significant. Note that the younger group had half as much time to respond as the elderly, which may have resulted in more omissions at the beginning of familiarization with the task.

**TABLE 2** Mean amplitude data of the analyzed ERP components in the younger and older age groups for the novel and repeated configurations (standard errors in parenthesis).

	Group	Configuration	P3	N2pc	sLRP	rLRP
Mean amplitude	Younger	Repeated	3.76 (1.19)	-1.3 (0.29)	-1.17 (0.22)	-2.1 (0.23)
		Novel	2.63 (0.12)	-0.76 (0.17)	-1.18 (0.13)	-2.11 (0.29)
	Older	Repeated	0.76 (1.07)	-0.56 (0.26)	-1.22 (0.18)	-4.19 (0.39)
		Novel	1.51 (1.05)	-0.57 (0.11)	-0.85 (0.21)	-4.09 (0.42)

Regarding RT, according to the GROUP main effect, the responses were generally slower in the older compared with the younger group,  $F(1,37)=85.891$ ,  $p<.001$ ,  $\eta_p^2=0.699$ . There was also a BLOCK main effect,  $F(5,185)=88.415$ ,  $p<.001$ ,  $\varepsilon=0.66$ ,  $\eta_p^2=0.705$ , where RT decreased over time. Post hoc tests showed that only Block 3 and Block 4, as well as Block 5 and Block 6, did not differ significantly from each other (both  $p=.406$ ). All other differences were significant ( $ps\leq.019$ ). The CONFIGURATION main effect was significant,  $F(1,37)=61.601$ ,  $p<.001$ ,  $\eta_p^2=0.625$ , with responses being faster for repeated compared with novel configurations. Most importantly, the interaction between BLOCK and CONFIGURATION was significant,  $F(5,185)=9.688$ ,  $p<.001$ ,  $\varepsilon=0.781$ ,  $\eta_p^2=0.208$ . Post hoc tests revealed that the repeated and novel configurations significantly differed from each other in all blocks ( $ps<.001$ ) except for Block 1 ( $p=1$ ). The remaining interactions were not significant.<sup>2</sup>

The similar error rates from Block 2 onward as well as the decreasing overall RT throughout the experiment suggest that the task was of similar difficulty for both age groups and that participants from both groups performed to the best of their abilities.

The analysis of the RT spatial contextual cueing effect revealed only a BLOCK main effect,  $F(5,185)=9.688$ ,  $p<.001$ ,  $\varepsilon=0.781$ ,  $\eta_p^2=0.208$ . The difference between the repeated and the novel configurations steadily grew as the task progressed and that change was comparable between groups. The post hoc analysis showed that Block 1 was significantly different from the rest of the blocks ( $ps\leq.016$ ), and that Block 2 was significantly different from Block 6 ( $p=.011$ ). No other significant differences were observed.

<sup>2</sup>The design of the experiment—sometimes the target and the required response were on the same side, and sometimes they were not—meant that the so-called Simon effect (Simon & Rudell, 1967) could modify the results. The Simon effect means that people are slower when the side of the target, and the side of the response are incongruent. We ran all behavioral analyses including target side—response side CONGRUENCE as an additional within-subject factor. Although there was a CONGRUENCE main effect, there were no meaningful interactions; thus, we collapsed across this factor in the analysis.

## 3.2 | ERP results

The descriptive statistics of the mean amplitudes for all components are summarized in Table 2.

### 3.2.1 | Comparing mean amplitudes

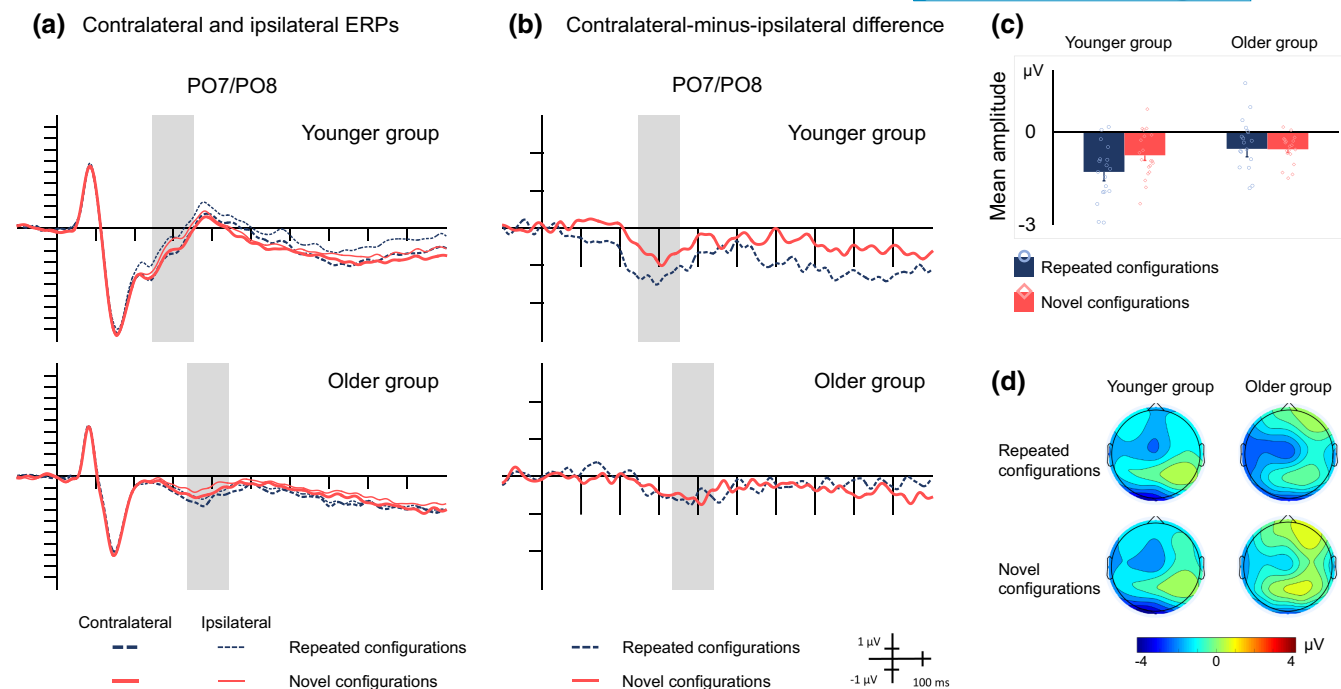
#### N2pc

The contra-ipsilateral difference potentials and scalp distributions are shown in Figure 4. The analysis of mean amplitudes revealed only a trend for the GROUP main effect,  $F(1,37)=3.792$ ,  $p=.059$ ,  $\eta_p^2=0.093$ . The mean amplitude was larger in the younger compared with the older group.

#### P3

The ERPs and scalp distributions are shown in Figure 5. The analysis of mean amplitudes showed a significant interaction between GROUP and CONFIGURATION,  $F(1,37)=23.667$ ,  $p<.001$ ,  $\eta_p^2=0.39$ . P3 was larger in the younger group for the repeated compared with the novel configurations ( $p=.001$ ) and tended to be larger in the older group for novel compared with repeated configurations ( $p=.059$ ).

N2. If we take a closer look at the ERPs in Figure 5, we can see that there is a difference in the central N2 component, after which the P3 component in the case of the repeated configurations does not reach the amplitude seen in the novel configurations, while the N2-P3 amplitude difference does not seem to differ in the case of the two contexts. To quantify this observation, in a post hoc analysis, we examined the N2 component at Fz, Cz, and Pz between 200 and 350 ms, and found a significant CONFIGURATION x GROUP interaction,  $F(1,37)=8.411$ ,  $p=.006$ ,  $\eta_p^2=0.185$ . Post hoc tests revealed only one significant difference: The amplitude was larger in the older group for the repeated rather than the novel configurations,  $t=-3.868$ ,  $p=.003$ , but a similar difference was not observed in younger adults (see Figure S4 in the Supplementary Material).



**FIGURE 4** N2pc. (a) Contralateral and ipsilateral ERPs and (b) Contralateral-minus-ipsilateral difference potentials at the PO8 and the PO7 electrode sites (averaged) in the younger (on top) and in the older (below) groups. The red continuous line shows the difference potential for novel configurations, and the blue dashed line shows the difference potential for repeated configurations. The thick lines in panel a show the contralateral ERPs and the thin lines show the ipsilateral ERPs. The gray area indicates the mean amplitude time window. (c) Mean amplitude in the younger and older groups. The red bars show the results for the novel configurations, and the blue bars show the results for the repeated configurations. Error bars show the standard errors, while the dots show the individual data. (d) Scalp distributions for repeated (on top) and novel (below) configurations in the younger (left) and in the older (right) group for the mean amplitude time window.

#### *Stimulus-locked lateralized readiness potential (sLRP)*

The contra-ipsilateral difference potentials and scalp distributions are shown in Figure 6. No significant main effects or interactions were found for mean amplitude.

#### *Response-locked lateralized readiness potential (rLRP)*

The contra-minus-ipsilateral difference potentials and scalp distributions are shown in Figure 7. For mean amplitudes, again only the GROUP main effect was significant,  $F(1,37) = 18.943$ ,  $p < .001$ ,  $\eta_p^2 = 0.339$ , with a larger amplitude in the older compared with the younger group.

### 3.2.2 | Relationship between the behavioral spatial contextual cueing effect and the spatial contextual cueing effect as observed in the ERPs

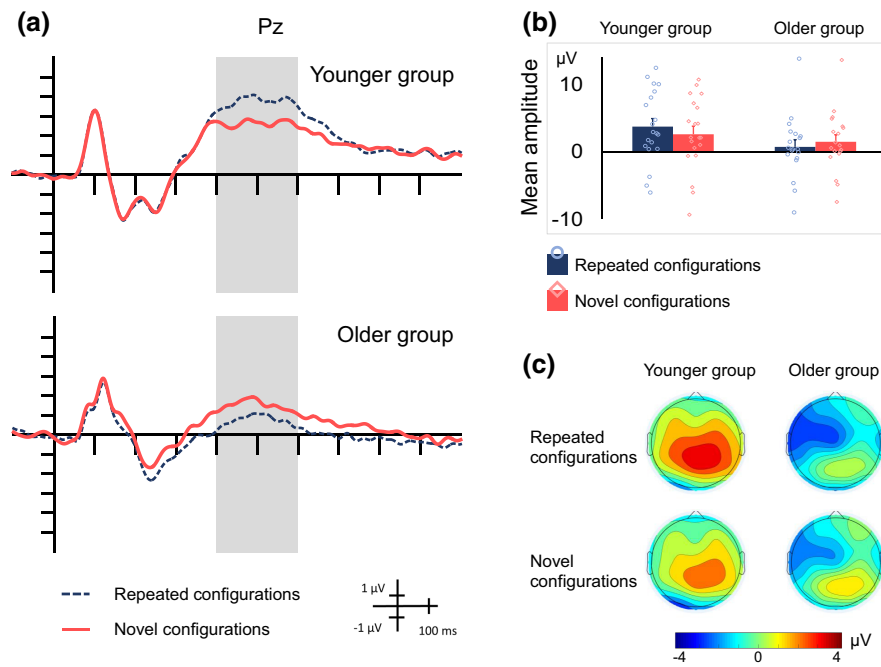
The correlations between the spatial contextual cueing effects in RT and in ERP are shown in Figure 8. In the younger group, the novel-minus-repeated difference in mean amplitude for N2pc correlated significantly with the novel-minus-repeated difference in RT,  $r = .462$ ,  $p = .04$ . The larger the spatial contextual cueing effect for RT, the larger

the N2pc was for repeated compared with novel configurations. The RT difference also correlated significantly with the novel-minus-repeated difference in mean amplitude for P3,  $r = -.607$ ,  $p = .005$ . The larger the spatial contextual cueing effect for RT, the larger the P3 was for repeated compared with novel configurations. These correlations were not significant in the older group,  $r = -.085$ ,  $p = .728$  and  $r = -.151$ ,  $p = .536$  for N2pc and P3, respectively. There were no other significant correlations in the younger group.

In the older group, only one correlation was significant. The novel-minus-repeated difference in mean amplitude for the rLRP correlated significantly with the novel-minus-repeated difference in RT,  $r = -.469$ ,  $p = .043$ . The larger the mean amplitude was for novel compared with repeated configurations, the larger the spatial contextual cueing effect. The same correlation was not significant in the younger group,  $r = -.008$ ,  $p = .974$ . No other correlations proved significant in the older group.

## 4 | DISCUSSION

The goal of the present study was to investigate the underlying mechanisms of the contextual cueing effect.



**FIGURE 5** P3 (a) Event-related potentials at the Pz electrode site in the younger (on top) and in the older (below) groups. The red continuous line shows the potential for novel configurations and the blue dashed line shows the potential for repeated configurations. The gray area indicates the mean amplitude time window. (b) Mean amplitude in the younger and older groups. The red bars show the results for the novel configurations and the blue bars show the results for the repeated configurations. Error bars show the standard errors, while the dots show the individual data. (c) Scalp distributions for repeated (on top) and novel (below) configurations in the younger (left) and in the older (right) group for the mean amplitude time window.

Attentional guidance and response facilitation, taken together, are the two major explanations for this effect. Another main goal was to explore whether the contextual cueing effect and the underlying mechanisms change with aging. We used ERP methodology, which is suitable to study on a fine time scale the processes involved.

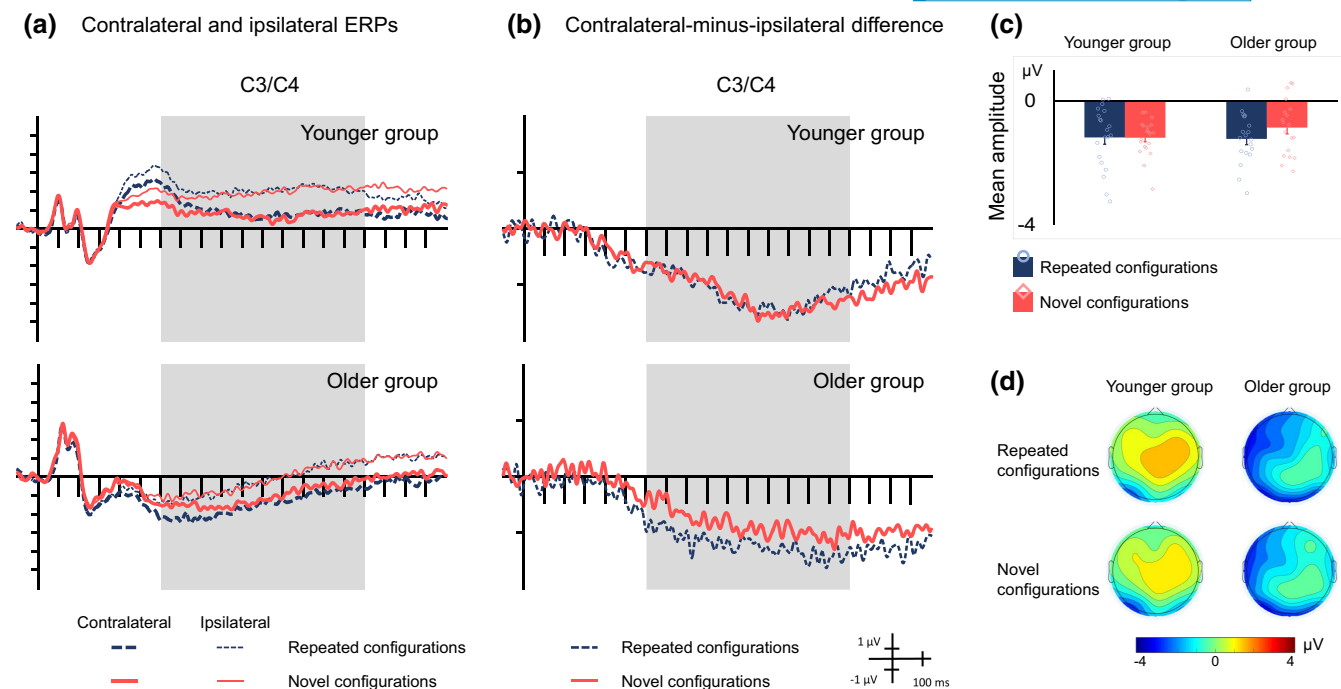
Firstly, we could replicate the behavioral results of the original Chun and Jiang (1998) study: while there were no RT differences in the first block—during the learning phase, when the initial encounters with the configurations were new for the participants. However, in the second block the RT became shorter for the repeated compared with the novel configurations, showing that the contextual effect had developed. Despite the elderly generally showing a slowing in their responses, this was not evident in the contextual cueing effect, where the RT difference between the two configurations did not differ between the age groups. This suggests that in our experiment, we were able to find an intact contextual cueing effect, which further supports those studies, where this form of implicit learning did not deteriorate with aging (Howard et al., 2004; Lyon et al., 2014).

Since we were particularly interested in what mechanisms are at work during the contextual cueing effect, we only targeted the ERP analysis from the second block

onward, as it was evident from then that this effect had already developed in both age groups. The N2pc component was our candidate for indicating attentional allocation. We expected that the amplitude would be larger for the repeated configurations, when compared to the novel, indicating that the participants' attention was shifted effectively to the side of the target stimulus in these cases (Johnson et al., 2007). Contrary to our expectations, in our study we found only a trend for the GROUP main effect, with a larger N2pc amplitude showing a more effective shift of attention to the target stimuli in the younger rather than the older group; but without the effect of CONFIGURATION.<sup>3</sup> A similar result was found by Schankin and Schubö (2009), who investigated this question further and correlated the amplitude differences

<sup>3</sup> Note that the N2pc in the younger group was somewhat smaller than what was observed in other studies (Johnson et al., 2007; Schankin & Schubö, 2009): It was approximately  $1 \mu\text{V}$  in the present study instead of  $2 \mu\text{V}$ . This may have been due to the longer presentation time: some configuration may contribute more to the spatial contextual cueing effect than others (Sisk et al., 2019), and longer presentation time may have emphasized the difference in contribution, which in turn could have caused the component to become more spread over time, reducing its amplitude. This may have similarly affected the older group; however, the smaller amplitude in that group could have been simply an age effect (see Introduction).



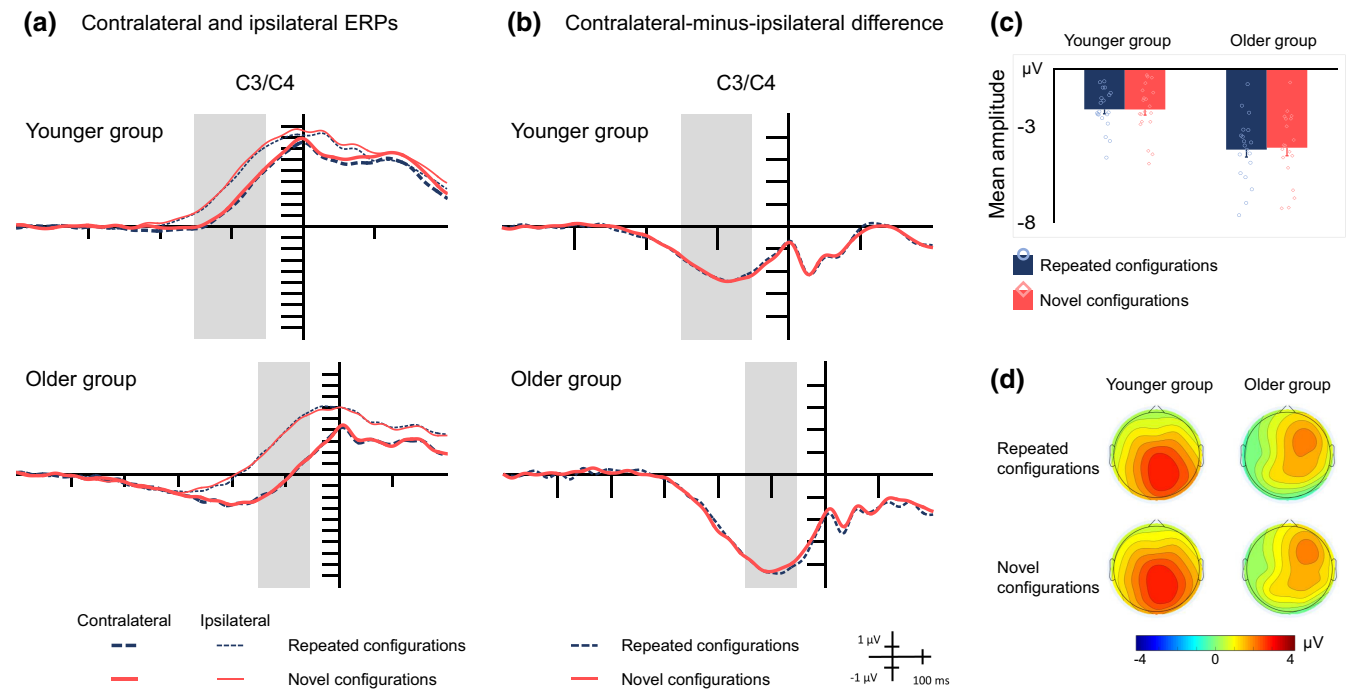


**FIGURE 6** sLRP (a) Contralateral and ipsilateral ERPs and (b) Contralateral-minus-ipsilateral difference potentials at the C4 and the C3 electrode sites (averaged) in the younger (on top) and in the older (below) groups. The red continuous line shows the difference potential for novel configurations, and the blue dashed line shows the difference potential for repeated configurations. The thick lines in panel A show the contralateral ERPs and the thin lines show the ipsilateral ERPs. The gray area indicates the mean amplitude time window. (c) Mean amplitude in the younger and older groups. The red bars show the results for the novel configurations, and the blue bars show the results for the repeated configurations. Error bars show the standard errors, while the dots show the individual data. (d) Scalp distributions for repeated (on top) and novel (below) configurations in the younger (left) and in the older (right) group for the mean amplitude time window.

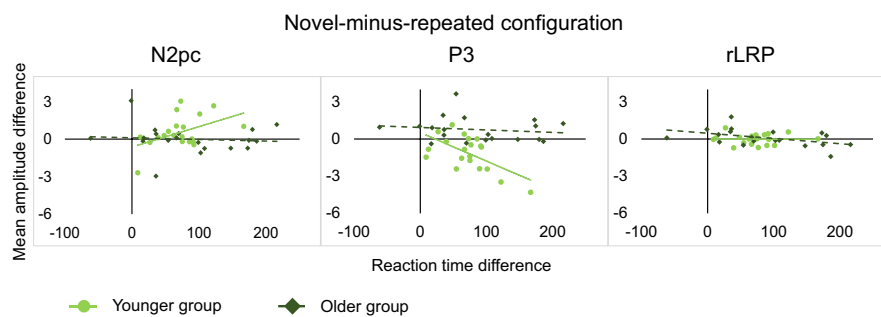
obtained for the two configurations with the RT differences. Repeating this step, we got similar results in younger adults: the larger the RT difference between the repeated and the novel configurations, the larger the amplitude of the N2pc in the repeated configuration compared with the novel. This means that in the younger group, when attention was effectively allocated to the side of the target stimulus, the contextual cueing effect appeared, supporting the attentional guidance account. We did not find such a correlation in the older group, which suggests that this mechanism was not responsible for the behaviorally observable effect in them. Thus, attentional allocation was more effective in the younger when compared to the older group, and early processes could contribute to the contextual cueing effect. Since a statistical learning occurs in this paradigm (Goujon et al., 2015), participants did not successfully predict the location of the target stimulus in all trials (as indicated by the initial section of the regression line on Figure 8, right), and this may have resulted in the GROUP  $\times$  CONFIGURATION interaction for the N2pc amplitude not reaching a significance level. Our results are also in line with the attentional selection assumption (Schankin & Schubö, 2010) for the role of N2pc in the contextual cueing effect. According to that assumption, N2pc to repeated configurations increases as

a result of participants being better at using contextual information either to suppress irrelevant information (Luck & Hillyard, 1994) or to enhance processing of the target (Eimer, 1996). Because inhibiting irrelevant stimuli is more challenging for older adults (Gaál et al., 2020; Kojouharova et al., 2020), our results could be interpreted as attentional selection contributing to the contextual cueing effect in younger but not in older adults. Nevertheless, there is some indication that an additional attentional process might be taking place in the older group. Because this process seems to influence the P3 component, we discuss it in the relevant section.

Although when looking for the underlying mechanisms, only an early and a late locus emerges in behavioral experiments (Sisk et al., 2019), using the ERP method allowed us to examine intermediate processes as well. The P3 component was studied in some experiments (Schankin & Schubö, 2009, 2010), and its amplitude was larger in the repeated compared with the novel configurations. We also found similar results in the younger age group. However, unlike Schankin and Shubö, who interpreted this component as an index of response-related processes, we would suggest that it is far from being clear to which processes this component can be connected. Among other possibilities, various studies have interpreted



**FIGURE 7** rLRP (a) Contralateral and ipsilateral ERPs and B: Contralateral-minus-ipsilateral difference potentials at the C4 and the C3 electrode sites (averaged) in the younger (on top) and in the older (below) groups. The red continuous line shows the difference potential for novel configurations, and the blue dashed line shows the difference potential for repeated configurations. The thick lines in panel (a) show the contralateral ERPs and the thin lines show the ipsilateral ERPs. The gray area indicates the mean amplitude time window. (c) Mean amplitude in the younger and older groups. The red bars show the results for the novel configurations, and the blue bars show the results for the repeated configurations. Error bars show the standard errors, while the dots show the individual data. (d) Scalp distributions for repeated (on top) and novel (below) configurations in the younger (left) and in the older (right) group for the mean amplitude time window.



**FIGURE 8** Correlations between the behavioral (RT) and the ERP spatial contextual cueing effects that reached statistical significance in at least one of the groups (left: N2pc mean amplitude; middle: P3 mean amplitude; right: rLRP mean amplitude). The light green continuous line shows the correlations in the younger group and the dark green dashed line shows the correlations in the older group. The dots show the individual data.

the increase in its amplitude as being: a successful template match (Chao et al., 1995; Squires et al., 1973) or another working memory process (Donchin & Coles, 1988; Polich & Criado, 2006); stimulus categorization (Johnson & Donchin, 1980); and closure of a perceptual epoch (Verleger, 1988). The amplitude is also influenced by factors such as subjective probability (Duncan-Johnson & Donchin, 1977; Kopp et al., 2016) of the stimulus; the amount of information transmission; and stimulus complexity (Johnson, 1986). With current research not able

to conclude which theory is correct in this visual search paradigm, our favored interpretation is that the larger amplitude for repeated compared with novel configurations indicates better predictability and greater decision confidence (Eimer & Mazza, 2005). Further research is necessary to clarify this question.

It is remarkable that the older adults also had different results to the younger group for this component: There was no significant difference between the amplitudes for the two configurations (in fact, it tended to be larger for

the novel configurations and not the repeated). However, there was a clear difference in amplitude between repeated and novel configurations for older adults in the preceding central N2 component: The mean amplitude for repeated configurations was larger. The statistical analysis showed that this difference was significant. The fact that the difference between the two configurations was observed in the central N2 and not in the N2pc component, may indicate that the repeated configurations did not direct the older adults' spatial attention, but their brain clearly recognized the repetition and reacted to it. Possible interpretations of the increase in N2 amplitude are that it indicates active attentional processes, with older adults paying more attention to the repeated trials which is in line with earlier studies showing the increased role of top-down attention in visual search tasks in older adults (Madden, 2007). Alternatively, they can inhibit the distractor stimuli more effectively in these trials (Falkenstein et al., 2002; Folstein & Van Petten, 2007; Priester & Wiswede, 2018).

It is a central issue in cognitive aging that older adults generally have difficulties with inhibiting irrelevant stimuli and therefore show poorer performance (Gaál et al., 2020). The contextual cueing effect is a form of implicit learning which improved performance for repeated configurations in this paradigm, and the increased N2 amplitude suggests that repeated spatial context may improve the inhibition of irrelevant stimuli and consequently, performance. As this attentional process could be observed in older but not in younger adults, there are two possible interpretations considering the attentional allocation and the attentional selection assumptions of N2pc. If N2pc reflects purely attentional allocation (i.e., a spatial aspect of attentional selection), our results suggest that attentional allocation is impaired in older adults and attentional selection (i.e., processes related to identification of the target stimulus) is employed to compensate for that. If N2pc reflects attentional selection (or a combination of attentional selection and attentional allocation); then, it is possible that there are two separate attentional selection processes, only one of which is preserved in older adults and takes over the role of the other. In this case, the decreased N2pc observed in the older group would suggest that attentional allocation and/or some attentional selection is preserved; however, bottom-up processing of distractor suppression is taken over by top-down inhibition of these stimuli. Although it was not our intention, our results suggest that the N2pc component reflects distractor suppression (filtering) rather than the shift of attention. Further research will help to shed light on this point.

However, the P3 component, unlike what we observed in the younger group, was not involved in the contextual cueing effect in the older adults. This latter assumption was also confirmed by the correlation of the RT and

P3 differences. A strong relationship was found in the younger group: the larger the contextual cueing effect the larger the P3 amplitude enhancement for the repeated configuration. We can interpret this as the more successful the stimulus categorization, template matching, or decision-making confidence, the faster the reaction. This correlation, however, was not observed in the older group. We can conclude from this that younger, as opposed to older adults involve brain mechanisms in facilitating the visual search that are active in the 400–600 ms time window after stimulus onset.

The third possible locus of the contextual cueing effect is that response-related processes become faster after implicit learning of the repeated configuration. We studied the response facilitation hypothesis via the s/rLRP components which reflect motor processes: selection, preparation, and execution of the response. We did not find significant differences in the amplitude of the sLRP component. The lack of an effect in our study is consistent with previous findings (Schankin & Schubö, 2009, 2010). The broader distribution of the component could be related to the broad distribution of RTs, which suggests that response selection processes varied in a wide time range, and thus, epoch averaging happened over a longer time window distorting the component. In the case of the rLRP, there was no effect of CONFIGURATION, and only age group differences were observed: the amplitude was larger in the older compared with the younger group. However, when we correlated the RT difference and rLRP amplitude difference in the two configurations, the older group showed a significant correlation, but not the younger one. Namely, the larger the RT difference between the repeated and the novel configurations, the smaller the amplitude of the rLRP in the repeated configurations compared with the novel. This result suggests that response preparation and/or execution was more effective for the repeated configurations, which could be the result of a decrease in the response threshold (Wild-Wall et al., 2008), and also, a late locus is involved in contextual cueing effect for older, but not the younger adults.

One might think that the longer stimulus presentation time in the older adults is a confound in our study. Nevertheless, it is a general method in aging studies to eliminate the effects of age-related slowing: It allows us to investigate how the processes involved in the solving of a task differ when performance is at the same level. The behavioral results of the two age groups were similar regarding error rates and decreasing RT; thus, task difficulty was similar across groups. How might the different presentation times have affected the ERP components? It did not seem to affect the elicitation of N2pc or the N2pc difference: eye movements commenced well

after the start of the component in both age groups, and even if older adults had more time to explore and memorize the display, this did not translate into an enhanced N2pc for repeated configurations. The start and peak of the P3 component were similar in the two age groups; thus, presentation time was an unlikely confound here as well. The sLRP results are consistent with the findings of previous studies, and if presentation time had led to more exploration and hence more variability, it affected the two groups in a similar way. Regarding the rLRP component, one could argue that the response-related processes would not have been modified in the older adults if presentation time had been shorter. However, in this case, due to aging effects, older adults would not have had sufficient time to gather enough information to achieve performance levels comparable to those of younger adults. Therefore, that would have also indicated an age-related effect. All in all, our results show that age-related differences in using different mechanism in this contextual cueing paradigm are unlikely to be due to different presentation times.

In summary, we found an intact contextual cueing effect at behavioral level in both age groups with different mechanisms being responsible for this, which in itself is a novel finding. In younger adults, we presume early attentional processes and effective stimuli identification in the time window of N2pc and P3 components are responsible for this; while in older adults, there is a shift from bottom-up to top-down processes, and both the inhibition of distractor stimuli and a more efficient response organization lead to a faster reaction.

### AUTHOR CONTRIBUTIONS

**Petia Kojouharova:** Conceptualization; data curation; formal analysis; methodology; project administration; software; visualization; writing – original draft; writing – review and editing. **Boglárka Nagy:** Conceptualization; formal analysis; methodology; writing – review and editing. **István Czizler:** Conceptualization; methodology; writing – review and editing. **Zsófia Anna Gaál:** Conceptualization; formal analysis; funding acquisition; methodology; project administration; supervision; writing – original draft; writing – review and editing.

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### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in OSF at <https://osf.io/r9nep/>.

### ETHICS STATEMENT

The study was approved by the United Ethical Review Committee for Research and Psychology (EPKEB), Hungary, and was carried out in accordance with the Declaration of Helsinki.

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### SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**Data S1.** The Supplementary Material contains details about the power analysis, an analysis regarding the eye

movements, additional analyses regarding N2pc and N2, the average number of epochs per condition, and a full summary of the statistical results.

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