Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: Effects on event-related brain potentials and performance data

Durk Talsma a,⁎, Albert Kok b, K. Richard Ridderinkhof b, c

a Cognitive Psychology Department, Vrije Universiteit, Van den Boechorststraat 1, 1081BT Amsterdam, The Netherlands
b Psychonomics Department, Universiteit van Amsterdam, The Netherlands
c Department of Psychology, Leiden University, Leiden, The Netherlands

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Abstract

To assess selective attention processes in young and old adults, behavioral and event-related potential (ERP) measures were recorded. Streams of visual stimuli were presented from left or right locations (Experiment 1) or from a central location and comprising two different spatial frequencies (Experiment 2). In both experiments, results were compared in visual-only and visual+auditory stimulus context conditions. Participants were forced to respond fast in both experiments, while maintaining high accuracy. In Experiment 1, no behavioral effects of aging were found; however, an enlargement of the N1 component in the older age group suggested that older adults initial selection process was larger than that of young adults. A late frontal effect following the P300 elicited by attended non-targets was larger in the visual+auditory condition than in the visual-only condition in the old age group. This effect was interpreted as reflecting a memory update of the relevant target location. In Experiment 2, older adults made relatively more errors in the visual+auditory condition than in visual-only condition, more so than the young adults. Older adults’ ERP data were also characterized by an enlargement of the occipital selection negativity, compared to the young age group. In contrast to experiment 1, no late frontal post-P3 effect could be found, suggesting that the memory trace of the relevant stimulus feature was updated less frequently, explaining the reduction in response accuracy in the visual+auditory stimulus context conditions.

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1. Introduction

One manifestation of cognitive aging is that older adults’ attentional capacity decreases (Greenwood and Parasuraman, 1994, 1997; Hartley, 1993; Kramer et al., 1994; McDowd and Birren, 1990; McDowd and Filion, 1992; McDowd and Shaw, 1999; Zeef and Kok, 1993). Selective attention is believed to be brought about in the brain by means of a biasing mechanism in sensory areas that is under the control of a supervisory network located in the association areas of the brain (LaBerge, 2001). This biasing mechanism is engaged in orienting the focus of attention toward relevant aspects of the environment, focusing it at one specific location (Posner, 1980) or stimulus feature (Giesbrecht et al., 2003; Slagter et al., 2005a,b).

The goal of the present study was to investigate whether differences in the capacity of the attentional system to stay focused on task-relevant stimulus items differed between younger and older adults. This was done by using event-related potentials (ERPs) to record the effects of an increasingly rich stimulus context in a spatial and a non-spatial visual attention task. ERPs are ideally suited to record the time course of brain processes related to attention, because they are evoked by attended and unattended stimuli alike. Visual selective attention ERP studies have consistently reported two sets of ERP effects in young adults: one for spatial selection and one for non-spatial selection. These findings are consistent with evidence on the existence of two specific pathways in the brain involved in the processing of.
object and location information, known as the ventral and dorsal pathways (Ungerleider and Mishkin, 1982). In addition, these findings support the idea that attentional selection processes are oftentimes believed to be contingent upon the spatial position of the attended stimulus (Van der Heijden, 1992, 1993).

In accordance with the literature demonstrating such a distinction between spatial and non-spatial attention, it has been suggested that spatial and non-spatial forms of attention are affected differentially by age. For example, Connelly and Hasher (1993) reported that the attentional selection of non-spatial stimulus information is more affected by age than spatial information. In addition, several researchers have found that spatial selection is relatively well preserved with increasing age (see Kok, 2000 for a review). One idea that has been established over the last decade is that a decrease in attentional selectivity in older age is due to a decline in inhibitory control functions, leading to a decrease in the ability to ignore irrelevant stimuli, specifically non-spatial stimuli (see Kok, 1999). It remains a question whether this is really the case, because most evidence has been obtained somewhat indirectly. To our knowledge, no aging study has yet investigated exactly this relationship between spatial and non-spatial attention on the one hand, and inhibition-related processes on the other hand, using a physiological index of the processing of attended and unattended stimuli.

The present paper addresses this question by presenting a study using adapted versions of two selective attention streaming tasks used earlier to study intermodal attention processes (Talsma and Kok, 2001, 2002). The design of these experiments also provided a suitable approach to study the effects of an increasingly rich stimulus environment on selective attention and age. In both studies, we manipulated the stimulus context by presenting either only stimuli of one modality (visual or auditory) at a time, or by randomly mixing these visual and auditory stimuli (visual + auditory stimuli) during a run of trials. We adopted these procedures for the present study by focusing specifically on the visual attention conditions, thus resulting in a visual-only and a visual + auditory experimental condition. In addition to being able to adopt previous experimental procedures, the use of auditory stimuli to increase the stimulus context was advantageous for a number of reasons. Firstly, the use of auditory stimuli had the advantage of keeping the visual perceptual load constant, thus allowing us to rule out any influence from visual processing as such on the attentional selection process. Secondly, auditory stimuli have been found to capture attention relatively easily, that is, they are presumed to be more difficult to be rejected or filtered out on the basis of their modality than visual stimuli (Schröger, 1996). Despite these properties, we could not conclude that in young adults these auditory stimuli did have a profound effect on the processing of visual stimuli in both non-spatial (Talsma and Kok, 2001) and spatial attention (Talsma and Kok, 2002). If, however, attentional selection mechanisms were affected by age, we would expect to find interactions between the young and the old age group on the degree to which they would be sensitive to the stimulus context, and ascribe these effects to a changed ability to ignore irrelevant stimuli in old age (see also Alain and Woods, 1999). In both experiments, participants were forced to respond fast, in order to maximize participants’ performance to the fullest. Previous studies have shown that when subjects were forced to respond fast, behavioral differences between young and old adults can be largely negated (Ratcliff et al., 2001, 2004). This approach would therefore essentially eliminate any strategy differences between young and old adults, and expose the true limits in attentional capacity.

Based on the results described above, we expected that if a decrease in attentional capacity with age is related to a relative inability to ignore (and thus inhibit the perception of) irrelevant stimuli, performance would decrease with an increasingly complex stimulus context. If, on the other hand, attention largely operates on the basis of increasing the perceptual sensitivity of relevant stimuli, we would expect that participants’ performance would be largely unaffected by the increasing complexity of the stimulus context. Furthermore, if it is indeed the case that non-spatial attention is more affected by age than spatial attention, we expected the age-related stimulus context effects to be stronger in a non-spatial attention task than in a spatial attention task.

2. Experiment 1: spatial attention

In this experiment, we sought to investigate whether the processes involved in focusing spatial selective attention are affected by age, and if so, to what degree. In particular, we investigated whether the ability of older adults to maintain their focus of attention would change when presented with increasing noise in the environment.

Spatial attention effects on the ERPs consist of initial amplitude enhancement effects of the early sensory P1 and N1 components, which mainly occur over the occipital and occipito-parietal areas. These two components are a reflection of the initial response of extrastriate areas to visual stimuli, and consist of an initial positive deflection around 80–100 ms (P1), which is followed by a negative deflection at around 180 ms (N1) after stimulus onset. Amplitude enhancement effects on these components were originally seen as reflecting a gain in the neural response to stimuli presented at the attended location (e.g., Eason, 1981; Hillyard et al., 1998; Wijers et al., 1996), but in more recent years, a functional distinction between the P1 and the N1 has been established (see Key et al., 2005 for a review).

Later ERP effects appear to be less domain (i.e., spatial vs. non-spatial) or modality (visual or auditory) specific, and have been shown to be sensitive to various attentional processes. For example, the N2b (a negative deflection at around 260 ms) is thought to reflect target difficulty (Senkowski and Herrmann, 2002). This component is usually followed by a P3b component (first discovered by Sutton et al., 1965), which is thought to be related to target identification. Although the P3b has been argued to reflect a number of related processes (Kok, 2001), the weight of evidence supports an interpretation in terms of updating a cognitive model of the environment in working
memory stores (Donchin and Coles, 1998). More or less orthogonal to the parietally distributed P3b, a frontally distributed P3a can oftentimes be triggered by novel stimuli (Squires et al., 1975). Usually, this component peeks somewhat earlier in time than the P3b, and it has been interpreted as reflecting the conscious orienting of attention toward a highly salient stimulus (Friedman et al., 2001).

We expected that, if older adults had more problems staying focused, this would result in decreases in behavioral performance as well as a reduction of the attentional selection effects in the ERPs. If cognitive aging affects the early stages of attentional selection, we expected to find attention-related differences between young and old adults on the early ERPs. If, however, these sensory processes remained relatively intact and if the interfering effects of stimulus context affected the later stages of processing, we would expect to find only effects of aging on the later stages of attentional selection, including the N2b, and P300 components.

2.1. Methods

2.1.1. Participants

Twenty-eight volunteers participated in the experiment (young age group: 18–35 years of age, mean 22, seven males and seven females; older age group: 60–79 years of age, mean 68, five males and nine females). All participants had normal or corrected-to-normal vision, as indicated by the Snellen charts for visual acuity, and good hearing, as assessed by both self-report and an on-site examination by the experimenter. In addition, all participants showed near perfect performance (i.e., more than 95% of all trials correct) on a visual discrimination task in which subjects were required to discriminate between horizontally and vertically presented gratings. In addition, all participants were in good mental and physical health, as indicated by an in-house developed screening form.

2.1.2. Stimuli

Streams of visual stimuli were presented in randomized order. These stimuli comprised white squares subtending a visual angle of about 2.3°, presented with equal probability to the left or right side of a visual display, at an angle of 15° from the center of fixation. Visual standard stimuli were presented with durations of 50 ms. In addition, a small proportion of the visual stimuli were presented with a longer duration of 200 ms, which were designated as targets (see below). In addition to the 105 standard duration visual stimuli that were presented for each stimulus type, in each task block, 35 longer-duration target stimuli were presented, totaling to 140 stimuli per location.

Auditory stimuli were sine waves with a frequency of 1000 Hz (65 dB(a), 50 ms duration, 10 ms linear rise and fall times) and were also presented with equal probability to the left and right, through speakers mounted to the sides of the display. Although care was taken to minimize the angle between the location of the visual and auditory stimuli (Eimer and Schröger, 1998), the auditory stimuli were presented at a slightly larger angle of about 16°.

2.1.3. Task description

Each block of trials lasted about 6 min. Participants were instructed to attend to the visual stimuli and were required to attend only to the stimulus at the designated location. The task contained two stimulus context conditions, hereafter referred to as the visual-only condition and the visual+auditory condition. In the visual-only condition, subjects received only visual stimuli (280 stimuli per run, 140 attended and 140 unattended), while in the visual+auditory condition the visual stimuli were interspersed with auditory stimuli (total of 560 stimuli per run, 140 attended, 140 unattended and 280 auditory stimuli). The stimulus onset asynchrony (SOA) between two successive stimuli varied randomly from 417 to 1234 ms in the visual-only condition. A random SOA was chosen to allow us to estimate the overlapping ERP components from adjacent trials (Woldorff, 1993; see below). In the visual+auditory condition, visual and auditory stimuli were randomly intermixed, and presented with SOAs that varied randomly between 417 and 817 ms. Because the randomization procedure allowed two visual stimuli or two auditory stimuli to be presented in succession, the difference in the maximum SOA between the visual-only and visual+auditory stimulus context yielded an approximately equal delivery rate of successive visual stimuli in the visual-only and visual+auditory stimulus conditions. The visual-only and visual+auditory conditions were administered in separate blocks of trials.

2.1.4. Apparatus

The visual stimuli were presented on a 21-in. VGA computer display, located at a distance of 56 cm, directly in front of the subjects’ eyes. Auditory stimuli were presented over two loudspeakers placed at the two sides of the computer screen. Stimulus presentation was controlled by a personal computer, running an in-house developed MS-DOS based application to ensure exact timing.

Electroencephalographic (EEG) signals were continuously recorded using 30 electrodes mounted in an electrocap. The locations used were Fpz, AFz, Fz, Cz, Pz, Oz, Fp1, Fp2, F7, F3, F4, F8, FC5, FC6, T7, C3, C4, T8, CP5, CP1, CP2, CP6, P7, P3, P4, P8, PO3, PO4, O1 and O2. The electrodes were referenced against an electrode attached to the subject’s right ear lobe. The impedance was kept below 5 kΩ. Horizontal eye movements were measured by deriving the electro-oculogram (EOG) from two electrodes placed to the outer canthi of the subjects’ eyes. Vertical eye movements and eye blinks were detected by deriving an EOG from two electrodes placed approximately one centimeter above and below the subject’s right eye. The EEGs and EOGs were amplified by a Nihon-Kohden Neurotop system and filtered using a 35 Hz low pass and a time-constant of 2.5 s. The registered signals were digitized with a sample frequency of 250 Hz and digitally stored for off-line analysis.

2.1.5. Procedure

The order in which the attention and stimulus context conditions were administered was randomly balanced across subjects. Each trial block was presented twice to each subject. A
new stimulus order was randomly generated before each session.

After attachment of the electrodes, subjects were given a number of practice trials, to ascertain that they understood the paradigm and to familiarize them with the stimulus material. Prior to each block of trials, participants were instructed to attend to one of the two locations and to detect target stimuli presented at that location. They were instructed to note these targets by means of a speeded button-press response. Participants were specifically instructed to respond as fast as possible, but they were also instructed to try and minimize their error rate. At the end of each trial block, participants received verbal feedback from the experimenter about their reaction times and hit rates and false alarm rates. Due to the relatively fast stimulus presentation rate, participants were forced to respond within one second after target onset; otherwise, a target response was considered incorrect. It was stressed that they respond only to the target stimulus appearing at the attended location and thus to minimize their error rates. Participants were further instructed to control eye blinks and bodily movements, and fixate on a centrally presented on-screen reference point. Eye movements were monitored using both the EOG and a TV camera to verify that the subjects maintained fixation.

2.1.6. Data analysis

2.1.6.1. Behavioral measurements. Average response times for correctly detected targets, as well as the percentage of hit rates and false alarms were calculated for each condition and subjected to an analysis of variance (ANOVA). This analysis contained the within-subjects factors location (two levels: attend left or attend right) and stimulus context (two levels: visual-only or visual + auditory stimuli). In all analyses, group (two levels: young vs. older adults) served as a between-subjects factor.

2.1.6.2. ERP averaging. During off-line analysis, time-locked epochs of 4096 ms (1024 samples) containing a pre-stimulus baseline of 1024 ms were selectively averaged. This relatively long epoch was chosen to facilitate the overlap correction procedure detailed below. Trials containing amplifier saturations, slow drifts of more than 40 μV/s or transient spike artifacts in excess of 150 μV/4 ms, were automatically excluded from the averaging procedures and ocular artifacts were corrected. Artifact detection and correction was done using the methods described in Talsma and Woldorff (2005). All ERP averages were subsequently corrected for possible overlap stemming from adjacent trial ERP activity using the ADJAR level 2 method (Woldorff, 1993). ERP analyses were confined to the standard (i.e., non-target) stimuli. This was done because the non-targets elicited by both the attended and unattended stimuli were unaffected by response selection and motor-response processes. Statistical analysis was conducted using mixed model analysis of variance. Where appropriate, the specific design of the tests is described in Section 2.2.

2.2. Results

2.2.1. Behavioral data

Statistically significant effects were found on neither reaction time nor on accuracy measures. This result indicates that both young and older adults were very capable of performing these tasks, and therefore we cannot conclude that they were affected by the presentation of the auditory stimuli. Mean response times and hit rates are given in Table 1.

2.2.2. Event-related potentials

2.2.2.1. P1 and N1 components. Initial visual inspection of the spatial task data suggested five consecutive phases of attention effects (see Fig. 1). These were (a) a parieto-occipital P1 enhancement (080–120 ms), (b) an occipital N1 enhancement (140–200 ms), (c) a temporal N2 effect (240–280 ms), (d) a parietal P3 enhancement (360–480 ms) and (e) a frontally distributed P3 enhancement (460–500 ms).

The P1 attention effect was determined by computing the peak voltages in a time window between 100 and 200 ms after stimulus onset, at the PO3 and PO4 electrodes. For right hemifield stimuli, the order of the PO3 and PO4 electrodes was inverted so that the first of the electrodes reflected the hemisphere ipsilateral to the field of stimulation, and the second electrode the hemisphere contralateral to the field of stimulation. These voltages were submitted to ANOVA with hemisphere (ipsi- or contralateral PO electrode), stimulus context (visual-only or visual + auditory) and attention (attended or unattended) as within-subjects factors, and group (young vs. older) as a between-subjects factor. A main effect of attention confirmed the classical P1 attention effect \[ F(1,26)=24.88, p<0.0001 \] and an interaction between group and hemisphere \[ F(1,26)=16.44, p<0.0005 \] confirmed that the contralaterality of the P1 was stronger in the old age group than in the young age group.

The occipital N1 attention effect was statistically tested using the same design as described above, but now using the peak voltages obtained on the electrodes O1 and O2, in the time window between 140 and 200 ms after stimulus onset. A main effect of group \[ F(1,26)=4.78, p<0.05 \] indicated that N1 components were slightly larger in the old age group than in the younger age group.

Table 1  Mean response times and hit rates as observed in Experiment 1 (spatial attention)

<table>
<thead>
<tr>
<th></th>
<th>Young adults</th>
<th>Older adults</th>
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<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
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<tr>
<td>Response times</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual-only</td>
<td>506 (70.5)</td>
<td>523 (74.1)</td>
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<tr>
<td>Visual + auditory</td>
<td>519 (81.5)</td>
<td>525 (67.7)</td>
</tr>
<tr>
<td>Hit rate</td>
<td></td>
<td></td>
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<tr>
<td>Visual-only</td>
<td>0.86 (0.11)</td>
<td>0.82 (0.17)</td>
</tr>
<tr>
<td>Visual + auditory</td>
<td>0.88 (0.14)</td>
<td>0.88 (0.11)</td>
</tr>
<tr>
<td>False alarm rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual-only</td>
<td>1.28 (1.2)</td>
<td>1.00 (0.8)</td>
</tr>
<tr>
<td>Visual + auditory</td>
<td>1.61 (1.5)</td>
<td>1.81 (1.8)</td>
</tr>
</tbody>
</table>

Standard deviations are given in parentheses.
Fig. 1. Event-related potential plots of the spatial attention effects in Experiment 1. Each tick mark on the x-axis equals 1007 ms. ERPs from left and right visual field stimuli were collapsed, after mirroring the left and right hemisphere electrodes for the right-hemisphere stimuli. Therefore, the leftmost electrodes of each graph represent the hemisphere ipsilateral to the field of stimulation, whereas the rightmost electrodes of each graph represent the contralateral hemisphere.
young age group. A main effect of hemisphere \(F(1,26)=11.38, p<0.002\) indicated that the N1 was larger over the contralateral hemisphere. Although a main effect of attention was just short of significance \(F(1,26)=3.19, p>0.05\); a significant interaction between attention and hemisphere \(F(1,26)=7.41, p<0.01\) indicated that the N1 elicited by attended stimuli was larger over the contralateral hemisphere. An interaction between attention and group \(F(1,26)=5.24, p<0.05\) indicated that the occipital N1 attention effects were stronger in the older age group. A significant interaction between stimulus context and attention \(F(1,26)=4.75, p<0.05\) indicated that the N1 enhancement effect was somewhat larger in the visual+auditory condition than in the visual-only condition. Finally, a trend toward a significant interaction between group, stimulus context, attention and hemisphere was found \(F(1,26)=3.86, p=0.06\).

2.2.2.2. N2 effects. Similarly, the temporal N2 attention effect was statistically tested using a design as described above, but now using the mean voltages obtained on the electrodes T5 and T6, in the time window between 220 and 260 ms after stimulus onset. A main effect of group just reached significance \(F(1,26)=4.20, p=0.05\). Furthermore, a significant main effect of attention \(F(1,26)=6.69, p<0.02\) demonstrated that the N2 following attended stimuli was larger than the one following unattended stimuli. Finally, a main effect of hemisphere \(F(1,26)=14.85, p<0.001\) showed that the N2 was larger over the hemisphere contralateral to stimulus presentation. No interactions involving group and attention were found.

2.2.2.3. P300 components. The P3b effect was tested by computing the mean voltage between 360 and 480 ms at the Pz electrode, and by subjecting these values to ANOVA with stimulus context (visual-only or visual+auditory stimuli), attention (attended or unattended) as within-subjects factors and group (young vs. older) as a between-subjects factor. A main effect of stimulus context \(F(1,26)=26.93, p<0.0001\) indicated that the P3b was significantly larger in the visual+auditory condition than in the visual-only condition. A significant main effect of attention \(F(1,26)=53.0, p<0.0001\) indicated that the P3b components elicited by attended stimuli were larger than those elicited by unattended stimuli. A significant interaction between the factors stimulus context and attention \(F(1,26)=4.28, p<0.05\) indicated that the P3 attention effect was larger in the visual+auditory condition than in visual-only condition. Finally, a significant interaction between group and attention \(F(1,26)=5.28, p<0.05\) indicated that the P3b attention effect was larger in the old age group than in the young age group.

The frontal P3 effect was assessed by computing the mean voltages between 460 and 500 ms at the ipsi- and contralateral F3 and F4 electrodes and by submitting these values to ANOVA. Hemisphere (ipsi- or contralateral frontal electrode), stimulus context (visual-only vs. visual+auditory) and attention (attended or unattended) served as within-subjects factors, and group (young vs. older) as a between-subjects factor in this design. A main effect of group \(F(1,26)=4.24, p<0.05\) confirmed that the frontal P3 was larger in the older age group than in the young group. In addition, a main effect of stimulus context \(F(1,26)=5.76, p<0.02\) confirmed that the frontal P3 was larger in the visual+auditory condition than in the visual-only condition. Similarly, a main effect of attention \(F(1,26)=17.74, p<0.0005\) showed that the frontal P3 was larger for attended than for unattended stimuli. A main effect of hemisphere \(F(1,26)=16.91, p<0.0005\) indicated that the frontal P3 was larger over the contralateral hemisphere. Finally, a significant three-way interaction between attention, stimulus context and hemisphere indicated that an attention-related increase in frontal P3 activity could be observed over the ipsilateral hemisphere, which was more pronounced in the visual+auditory condition than in the visual-only condition.

2.2.2.4. Late effects. Interestingly, following the peak of the frontal P3 effects described above, we found another significant effect that appeared to be larger over the ipsilateral hemisphere. The analysis of this ipsilateral fronto-central effects (using mean amplitudes between 520 and 580 ms, obtained from the ipsilateral C3 and C4 electrodes; see Fig. 2), revealed not only significant main effects of group \(F(1,26)=12.0, p<0.001\), stimulus context \(F(1,26)=15.90, p<0.0001\) and attention \(F(1,26)=24.4, p<0.0001\), but also an interaction between group and attention \(F(1,26)=22.6, p<0.0001\), and a significant three-way interaction between group, stimulus context and attention \(F(1,26)=6.08, p<0.05\).

2.3. Discussion

This experiment investigated whether the ability to focus attention changes with age, specifically in an increasingly rich stimulus context. The main findings from this experiment are that although no effects on behavioral performance data could be found, older adults' physiological effects of attention differed from those of the younger participants. These effects included an enlargement of the contralateral N1, P3b and an additional frontal attention effect following the frontal P3. The latter component was larger over the ipsilateral hemisphere relative to the attended location, and in particular in older adults, larger in the visual+auditory conditions than in the visual-only conditions.

The behavioral results in this experiment show that older adult’s performance did not differ significantly from that of the younger participants, indicating that older adults were successfully motivated to respond as fast and accurately as possible. These findings would be consistent with the earlier notion that spatial attention might be relatively spared in older adults, relative to attending to non-spatial forms of attention (Connelly and Hasher, 1991; Hartley et al., 1990; Hartley et al., 1992; Nissen and Corkin, 1985; Tipper et al., 1990), suggesting that processing in the phylogenetically older dorsal pathway is less sensitive to cognitive aging than the ventral pathway.

The ERP data, however, contrast this idea by showing that a first attention-related difference occurs at around 140–200 ms after stimulus onset. Interestingly, whereas the N1 component was modulated differentially by attention in the young and the
old age group, the preceding P1 component was not. Although initially the modulations of the P1 and N1 component were interpreted as a unitary “sensory gain” effect (Hillyard et al., 1998; Wijers et al., 1996), contemporary research is revealing different functional properties of the P1 and N1 components. The P1 is believed to reflect the initial encoding of incoming (non-spatial) visual information such as color and shape of stimuli in extrastriate cortex (Mangun et al., 1993). Mangun et al. also showed that the N1, on the other hand, is more explicitly related to an enhanced processing of the attended location, including the spatial properties of the attended stimulus. In addition, whereas the P1 has been hypothesized to be sensitive to the suppression of noise, the N1 has been found to be particularly sensitive to attention. The P1 amplitude has been shown to decrease for unattended locations, but not to further increase for attended locations, relative to a neutral baseline condition. For the N1 component, the opposite pattern has been found: the N1 elicited by attended stimuli was larger relative to a baseline condition, whereas the N1 elicited by unattended stimuli did not further decrease relative to the baseline (Luck et al., 1994; Mangun, 1994; Talsma et al., 2005). The results in our present study therefore suggest that the attentional selection processes related to spatial information (i.e., as reflected in the N1 component) were enhanced in older adults.

We could not firmly conclude that interference from auditory stimuli affected these early components, despite a trend toward a significant interaction between group, stimulus context, attention and hemisphere. Nevertheless, a significant influence of the auditory stimuli did manifest itself at longer latencies. Because overlapping ERP responses from the auditory stimuli were removed from the visual ERPs, and also because the visual and auditory stimuli were always presented more than 400 ms apart, we can rule out any direct (phasic) distraction of the auditory stimuli on the visual ones (i.e., as would be caused by presenting auditory stimuli directly before or after the visual stimulus (see e.g., Escera et al., 2000). Therefore, the distraction induced in the present experiment is of a more tonic nature, which would presumably place a much greater demand on the attentional control systems to stay focused during an entire block of trials. The timing as well as the relatively fronto-central to frontal effects suggest that these late effects reflect indeed an increase of the attentional control mechanism to stay focused on the relevant stimulus. Since this effect appears specifically tied to visual stimuli presented at the attended location, we propose that this effect might reflect a re-enforcement or memory updating process that actually makes use of visual stimuli at the attended locations to keep the attentional controller focused. Such an updating of working memory processes is also one of the classical interpretations of the P3b component (Donchin and Coles, 1988), the amplitude of which also interacted with age and attention in the present experiment. However, only the frontal late effect following the P3b interacted with stimulus context, suggesting that this was indeed an additional process evoked by the additional stimulus context.

Taken together, the data from Experiment 1 show that, while spatial attention appeared to be relatively resilient against the influence of cognitive aging, the electrophysiological data revealed that these processes were sensitive to age. Enhancements of the spatial attention-related early ERP components suggest that early spatial processing is in fact strongly sensitive to attention in older adults, but that at later stages of cognitive processing, a greater compensatory effort is required to stay focused.
3. Experiment 2: non-spatial attention

To address the question of whether non-spatial forms of attention would be more susceptible to the aging process, a second experiment was run, in which we instructed subjects to selectively attend to non-spatial stimulus attributes. In Experiment 2, ERPs were recorded that were elicited by attended and unattended visual line gratings, in the presence or absence of distracting tones.

The early ERP waveforms related to non-spatial attention differ somewhat from that of those elicited in spatial attention experiments. The most pronounced non-spatial attention effect occurs somewhat later in time than the spatial P1 and N1 modulations and consists of a negative displacement of the occipital attended ERP waveform, which occurs around 160–200 ms after stimulus onset. This effect, known as the ‘selection negativity’, is commonly interpreted as a signature of selective attribute processing of a visual stimulus following selection (Anllo-Vento and Hillyard, 1996; Smid et al., 1999). In addition, between about 150 and 200 ms, a frontal ‘selection positivity’ is commonly observed (Heslenfeld et al., 1997; Kenemans et al., 1995; Michie et al., 1999). Both of these non-spatial components have been shown to be sensitive to aging (Kenemans et al., 1995). Later ERP component are less sensitive to the distinction between spatial and non-spatial attention.

The results of the Kenemans et al. (1995) study showed decreases in the amplitude of the occipital selection negativity and the frontal selection positivity. An interesting question is if we still would find such decrease of these components when older adults were forced to respond fast, since Experiment 1 had shown that the early spatial N1 attention effect was actually larger for the old than for the young group. If older adults’ capacity to keep their attention focused on non-spatial stimulus features is weaker than in young adults, we would indeed expect smaller selection negativities, as well as smaller amplitude effects on the later components, specifically in the visual +auditory stimulus context, due to the added noise of the environment. If, on the other hand, subjects could also compensate for the high task demands, we would expect a similar pattern of results as in Experiment 1.

3.1. Methods

3.1.1. Participants

The same participants that were reported in Experiment 1 volunteered in this study. For details, we refer to the description given for Experiment 1.

3.1.2. Task and stimuli

The general procedure for this experiment was the same as the one reported for Experiment 1. The main difference between Experiments 1 and 2 was that stimuli were now presented centrally. The visual stimuli consisted of white rectangular horizontal square-wave gratings, with a spatial frequency of 3.2 cycles per degree for the high spatial frequency gratings and 0.8 cycles per degree for the low spatial frequency. The values used are known to elicit the largest differences in their exogenous effects (Previc and Harter, 1982).

The auditory stimuli consisted of sine waves, with a frequency of 900 Hz for the low-pitched tones and 2000 Hz for the high-pitched tones. Tones were presented at 65 dB(A) and had linear rise and fall times of 10 ms. Gratings and tones were presented randomly with equal probability and lasted for 50 ms. In addition, a small proportion of the visual stimuli were presented with a longer duration of 200 ms, which were designated as targets. In addition to the 105 standard duration visual stimuli that were presented for each stimulus type, in each task block, 35 longer-duration target stimuli were presented, totaling to 140 stimuli per spatial frequency. Visual stimuli were presented at the central location (point of fixation) on a computer screen, and auditory stimuli were presented simultaneously over two loudspeakers that were mounted to the horizontal edges of the screen, creating the subjective impression that the tones were presented from the same center location as the visual stimuli. This procedure minimized the use of spatial information about the location of relevant and irrelevant stimuli (Eimer and Schröger, 1998).

The task also contained two stimulus context conditions. In the visual-only condition, subjects received only visual stimuli (280 stimuli per run, 140 of the relevant spatial frequency and 140 of the irrelevant), while in the visual +auditory condition the visual stimuli were interspersed with auditory stimuli (total of 560 stimuli per run, 140 relevant spatial frequency, 140 irrelevant spatial frequency and 280 auditory stimuli). The stimulus onset asynchrony (SOA) between two successive stimuli varied randomly between 417 and 1234 ms in the visual-only condition. A random SOA was chosen to allow us to estimate the overlapping evoked potential components from adjacent trials (Woldorff, 1993). In the visual +auditory condition, these visual and auditory stimuli were randomly intermixed, and presented with SOAs that varied randomly between 417 and 817 ms. Because the randomization procedure allowed two visual stimuli or two auditory stimuli to be presented in succession, the difference in the maximum SOA between the visual-only and visual +auditory stimulus yielded an approximately equal delivery rate of successive visual stimuli in the visual-only and visual +auditory stimulus conditions.

3.1.3. Procedure

The order in which the attention and stimulus context conditions were administered was randomly balanced across subjects. As in Experiment 1, each trial block was presented twice to each subject and a new stimulus order was randomly generated before each session.

Prior to each block of trials, participants were instructed to attend to one of the designated spatial frequencies, and to detect target stimuli of that frequency. They were instructed to report these targets by means of a speeded button-press response. Participants were specifically instructed to respond as fast as possible. At the end of each trial block, participants received verbal feedback from the experimenter about their reaction times and hit rates and false alarm rates. During the experiment, they were instructed to respond only to the target stimulus
containing the relevant spatial frequency, and thus to minimize their error rates. As in Experiment 1, participants were forced to respond within one second after target onset; otherwise, a target response was considered incorrect. Participants were further instructed to control eye blinks, and bodily movements and fixate on a centrally presented on-screen reference point. Eye movements were monitored using both the EOG and a TV camera to verify that the participants maintained fixation. Experiment 2 was run on the same day as Experiment 1.

3.1.4. Data analysis

3.1.4.1. Behavioral measurements. Similar to Experiment 1, average response times for correctly reported targets, as well as the percentage of hit rates and false alarms were calculated per condition and subjected to an analysis of variance (ANOVA). This analysis contained the within-subjects factors feature (two levels: visual-only vs. visual + auditory) and stimulus context (two levels: visual-only vs. visual + auditory). In all analyses, group (two levels: young vs. older adults) served as a between-subjects factor.

3.1.4.2. ERP averaging. The same ERP averaging, artifact and overlap correction procedures were used as described for Experiment 1. Again ERP analyses were confined to the standard (i.e., non-target) stimuli to allow a direct comparison between attended and unattended stimuli and statistical analysis was conducted using mixed model analysis of variance. The specific design of each test is described in Section 3.2, where appropriate.

3.2. Results

3.2.1. Behavioral data

Mean response times, hit rates and false alarm rates are given in Table 2. A statistically significant effect of stimulus context was found on response times \[ F(1,26)=4.46, p<0.05 \], demonstrating that, on average, the visual + auditory condition was more difficult than the visual-only condition. In addition, a significant three-way interaction between group, feature and stimulus context was found \[ F(1,26)=2.76, p<0.05 \], showing that older adults were somewhat slower in detecting the low spatial frequency targets, especially in the visual + auditory conditions.

Analysis of the hit rates revealed a similar pattern of results. Here, a significant interaction between group and stimulus context was found \[ F(1,26)=3.07, p<0.05 \], indicating that older adults’ tended to miss more targets in the visual + auditory condition than in the visual-only condition, in comparison to young adults.

3.2.2. Event-related potentials

Visual inspection of the grand average waveforms (Fig. 3) suggested the following effects: (a) a frontal selection positivity around 100–300 ms; (b) an occipital selection negativity which was most pronounced bilaterally over the occipital areas, between about 280 and 380 ms after stimulus onset; (c) P3b, peaking over Pz, at around 340 to 460 ms; and (d) a frontal P3 component with a scalp maximum over Fz, peaking at around 360–480 ms.

3.2.2.1. Frontal selection positivity. The frontal selection positivity effect was analyzed by computing the mean amplitude over a 200 ms time window, between 100 and 300 ms, at electrodes AFz and Fz, and subjecting these values to ANOVA with the factors site (AFz or Fz), stimulus context (visual-only vs. visual + auditory) and attention (attended or unattended) as within-subject factors, and group (young vs. older) as a between-subjects factor.

A highly significant main effect of attention was found \[ F(1,26)=17.57, p<0.0005 \], which indicated that the ERPs elicited by attended stimuli were positively displaced relative to the unattended stimuli. In addition, a significant main effect of stimulus context \[ F(1,26)=24.71, p<0.0001 \] indicated that the frontal selection positivity was markedly larger in the visual + auditory condition than in the visual-only condition. Two further effects were just short of significance, notably (a) the main effect of group \[ F(1,26)=3.19, p=0.08 \] and (b) the interaction between group and attention \[ F(1,26)=3.17, p=0.08 \].

3.2.2.2. Occipital selection negativity. The occipital selection negativity was analyzed using a similar design as described above, but was quantified by computing the mean amplitude between 280 and 380 ms after stimulus onset on electrodes O1 and O2. A highly significant main effect of attention \[ F(1,26)=49.32, p<0.0001 \] confirmed the existence of this effect. This selection negativity was larger in the older than in the younger age group, as evidenced by an interaction between group and attention \[ F(1,26)=5.13, p<0.03 \].

3.2.2.3. P300 effects. The posterior P3 effect was statistically tested at the Pz electrode, by computing the mean amplitude between 400 and 500 ms, and subjecting these voltages to ANOVA with stimulus context (visual-only vs. visual + auditory) and attention (attended or unattended) as within-subject factors, and group (young vs. older) as a between-subjects factor. A main effect of stimulus context \[ F(1,26)=31.37, p<0.0001 \] confirmed that this P3b was larger in the

### Table 2

Mean response times and hit rates as observed in Experiment 2 (non-spatial attention)

<table>
<thead>
<tr>
<th></th>
<th>Young adults</th>
<th>Older adults</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low spatial frequency</td>
<td>High spatial frequency</td>
</tr>
<tr>
<td>Response times</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual-only</td>
<td>481 (53.6)</td>
<td>481 (61.5)</td>
</tr>
<tr>
<td>Visual + auditory</td>
<td>501 (91.7)</td>
<td>485 (76.7)</td>
</tr>
<tr>
<td>Hit rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual-only</td>
<td>0.89 (0.04)</td>
<td>0.87 (0.12)</td>
</tr>
<tr>
<td>Visual + auditory</td>
<td>0.91 (0.09)</td>
<td>0.93 (0.10)</td>
</tr>
<tr>
<td>False alarm rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual-only</td>
<td>1.30 (0.9)</td>
<td>1.6 (1.1)</td>
</tr>
<tr>
<td>Visual + auditory</td>
<td>2.04 (1.5)</td>
<td>2.19 (1.7)</td>
</tr>
</tbody>
</table>

Standard deviations are given in parentheses.
Fig. 3. Event-related potential plots of the non-spatial attention effects in Experiment 2. Each tick mark on the x-axis equals 100 ms.
visual+auditory condition than in the visual-only condition. In addition, a significant main effect of attention \([F(1,26)=17.34, p<0.0005]\) showed that the P3b components elicited by attended stimuli were larger than the ones elicited by unattended stimuli. Somewhat surprisingly, a main effect of group \([F(1,26)=7.58, p<0.001]\) showed that the P3b was significantly larger in the old age group than in the young age group. Interestingly, the attention effect on the P3b was also larger in the old age group than in the young age group, as shown by a significant interaction between group and attention \([F(1,26)=5.50, p<0.05]\).

The frontal P3 effects were statistically tested by computing the mean amplitude at electrodes F3 and F4 between 360 and 480 ms and subjecting these values to ANOVA, with site (F3 or F4), stimulus context (visual-only vs. visual+auditory) and attention (attended or unattended) as within-subject factors, and group (young vs. older) as a between-subjects factor. The following effects were found in this analysis: First, a main effect of stimulus context \([F(1,26)=59.0, p<0.0001]\) demonstrated that the frontal P3 was significantly larger in the visual+auditory condition than in the visual-only condition. Second, a main effect of attention \([F(1,26)=5.92, p<0.05]\) showed that the frontal P3 elicited by attended stimuli was larger than the ones elicited by unattended stimuli. Third, a significant interaction between group and attention \([F(1,26)=13.39, p<0.001]\) showed that the attention effect on the frontal P3 was significantly larger in the older than in the young age group.

Finally, as for Experiment 1, we found that the frontal P3 was followed in time by a later effect that was mainly found over the left hemisphere (see Fig. 4). Here this effect appeared to occur somewhat later in time and therefore this effect was analyzed by computing the mean voltage between 580 and 620 ms after stimulus onset on the F3 electrode and submitting these values to ANOVA with stimulus context (visual-only or visual+auditory) and attention (attended or unattended) as within-subject factors, and group (young vs. older) as a between-subjects factor.

This analysis revealed significant main effects of stimulus context \([F(1,26)=9.63, p<0.005]\) and attention \([F(1,26)=43.61, p<0.0001]\), as well as interactions between group and attention \([F(1,26)=16.85, p<0.0002]\), and stimulus context and attention \([F(1,26)=7.59, p<0.01]\). However, the three-way interaction between group, stimulus context and attention \([F(1,26)=1.668, p>0.2]\) suggested by Fig. 4 could not be found.

3.3. Discussion

In contrast to Experiment 1, in Experiment 2, behavioral performance was affected by the stimulus context conditions. In addition, older adults’ performance was significantly more affected by stimulus context conditions than younger adults’ performance. This latter result is consistent with the hypothesis that the ability to ignore spatial forms of information remains relatively more intact with increasing age than the ability to ignore non-spatial forms of information.

Physiological results showed that the occipital selection negativity was substantially larger in older adults than in young adults. This result contrasts with earlier findings showing that the selection negativity was reduced in amplitude in older adults (Kenemans et al., 1995), from which these authors concluded
that non-spatial attentional capacity decreased with age. The present study differs in some important ways from the Kenemans et al. study, however. We used a much higher stimulus presentation rate and forced participants to respond as quickly as possible. In addition, we also did not find an overall main effect of age on reaction times, whereas Kenemans et al. did. An enlargement of the occipital selection negativity would be consistent with the results from Experiment 1, where we also found an enlargement of the contralateral N1 component, while older participants’ overall performance equaled that of the younger performance. A possible explanation for the enlargement of the processing negativity is thus that it reflects a larger compensatory effort to deliver the required high task performance.

Interestingly, attention effects on both the posterior and frontal P3 components were larger in the old age group than in the young age group. These age effects on the later P3 components were subtly different to what we found in Experiment 1. Whereas in Experiment 1 significant interactions involving the factors group and attention were found on the posterior P3b and the late wave following the frontal P3, in Experiment 2, an interaction between group and attention could be found on the P3b and the frontal P3 but not on the late effect. These results imply that an additional process is active during the processing of spatial information, with non-spatial processing presumably resulting in a less frequent updating of working memory context than during spatial processing.

These differences could possibly explain why the performance of older adults is somewhat weakened in the non-spatial visual + auditory condition in comparison to the visual-only condition. Because subjects were less often reminded of the relevant stimulus feature, the working memory representation was less often updated, which would in turn lead to a greater distraction by added auditory stimuli.

4. General discussion

The aim of the present study was to examine to what extent older adults’ attentional performance was affected by increases in task demands induced by task-irrelevant stimuli, and to what degree this differed between spatial and non-spatial forms of attention. To investigate this, we inserted auditory stimuli into a stream of ongoing attended and unattended visual stimuli. A novel finding in this study is that, whereas older adults’ performance was modulated by the visual-only vs. visual + auditory manipulation in the non-spatial task, their ERPs revealed the strongest effects in the spatial task.

The general pattern of results from the present study indicate that although people of 60 years of age or older are still relatively well capable of performing simple selective attention tasks, their performance on the non-spatial task decreased with an increasingly complex stimulus context, whereas their performance remained at the same level in the spatial task. ERP data offered more insights into the dynamics of the selective attention processes. First, differences in the amplitude of the N1 component (Experiment 1) and the occipital selection negativity (Experiment 2) showed that both spatial and non-spatial feature selection is affected by age. Because high demands were placed on the participants by forcing them to respond fast, we propose that these early increases in attention effects reflect a compensatory effort to keep the performance levels at a much higher level than what was previously required in aging studies. The amplitude increase of the frontal P3 component following attended stimuli in the spatial task suggests that older subjects may have used the spatial location of a task-relevant stimulus as a salient cue to reorient their attention after they had been distracted by irrelevant stimuli. Taken together, these processes could also explain why older adults are relatively impaired on non-spatial tasks. In these tasks, both relevant and irrelevant stimuli are presented at the same location, and for this reason cannot be used as a salient cue to reorient attention.

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