

Early Auditory Evoked Potential Is Modulated by Selective Attention and Related to Individual Differences in Visual Working Memory Capacity

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Abstract

■ A growing body of research suggests that the predictive power of working memory (WM) capacity for measures of intellectual aptitude is due to the ability to control attention and select relevant information. Crucially, attentional mechanisms implicated in controlling access to WM are assumed to be domain-general, yet reports of enhanced attentional abilities in individuals with larger WM capacities are primarily within the visual domain. Here, we directly test the link between WM capacity and early attentional gating across sensory domains, hypothesizing that measures of visual WM capacity should predict an individual's capacity to allocate auditory selective attention.

To address this question, auditory ERPs were recorded in a linguistic dichotic listening task, and individual differences in ERP modulations by attention were correlated with estimates of WM capacity obtained in a separate visual change detection task. Auditory selective attention enhanced ERP amplitudes at an early latency (ca. 70–90 msec), with larger P1 components elicited by linguistic probes embedded in an attended narrative. Moreover, this effect was associated with greater individual estimates of visual WM capacity. These findings support the view that domain-general attentional control mechanisms underlie the wide variation of WM capacity across individuals. ■

INTRODUCTION

Working memory (WM) capacity is a particularly powerful metric of individual cognitive differences, predicting “higher-level” outcomes such as fluid intelligence and scholastic achievement (e.g., Cowan et al., 2005), as well as “lower-level” sensory motor abilities such as saccade control (Kane, Bleckley, Conway, & Engle, 2001) and visual spatial attention (Fukuda & Vogel, 2009, 2011; Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003). Much evidence suggests that this relationship between WM capacity and cognitive ability is not because of variance in the amount of available storage space per se, but rather individual differences in the ability to control attention (e.g., Unsworth & Spillers, 2010; Kane et al., 2001), with the key assumption being that systems underlying this attentional control operate equivalently across different sensory domains (Unsworth & Engle, 2007a; Engle & Kane, 2004). Indeed, domain-general processing has been reported within the frontoparietal network implicated in WM and attention (see Janata, Tillmann, & Bharucha, 2002): in particular, coordination between the pFC and BG (McNab & Klingberg, 2008) influences online storage in the capacity-limited intraparietal sulcus (Xu & Chun, 2006; Todd & Marois, 2004).

There are few reports linking WM capacity with attentional capabilities outside the visual modality, and what research has been done employed complex span measures of WM shown to be susceptible to individual differences in memory retrieval strategies (Unsworth & Engle, 2007b). Conway and colleagues found that individuals with higher WM spans were less likely to detect their own name in an unattended auditory channel (Conway, Cowan, & Bunting, 2001), but this effect was reversed when participants were clued to the possible presence of their name (Colflesh & Conway, 2007). Additionally, Sörqvist and colleagues have reported relationships between span scores and auditory attention during concurrent memory tasks (Sörqvist, Nöstdl, & Halin, 2012; Sörqvist, Stenfelt, & Rönnerberg, 2012; Sörqvist, 2010). A recent ERP study reported that greater reading span performance correlated with reduced auditory N1 amplitude evoked by distractors in an oddball task, but N1 amplitudes were also reduced for targets, making it unclear whether these effects reflected enhanced control of auditory attention or a more general mechanism such as arousal (Tsuchida, Katayama, & Murohashi, 2012). Although these studies implicate WM capacity in the control of auditory attention, they do not show a robust relationship between WM and early sensory gating processes as has been demonstrated in the visual domain (i.e., Fukuda & Vogel, 2009, 2011).

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Here, we tested the domain generality of attention control mechanisms associated with WM by measuring WM capacity in a visual change detection task (Luck & Vogel, 1997) and examining its relationship with attentional modulation of auditory ERPs elicited during a task designed to emphasize early selection (Coch, Sanders, & Neville, 2005). In the first experiment, we found that auditory spatial attention increases the amplitude of ERP components as early as the P1 component (latency 70–90 msec). In a second experiment, we replicated and extended these findings by documenting a relationship between individual differences in auditory attention and visual WM.

METHODS

Participants

All participants were students at the University of Oregon who volunteered in exchange for course credit and gave informed consent to procedures approved by the Office for Protection of Human Subjects. A different group of participants was recruited for each experiment, with 22 participants in Experiment 1 (13 women; age $M = 20.4$ years, $SD = 2.2$) and 22 participants in Experiment 2 (13 women; age $M = 19.1$ years, $SD = 1.5$). All were right-handed, native English-speakers, with no history of neurological disorders, hearing impairment, or learning disabilities, and all had normal or corrected-to-normal vision.

Auditory Selective Attention Task

General Procedure

All experimental sessions began with participants performing an adaptation of a classic auditory spatial selective attention ERP task (e.g., Woods, Hillyard, & Hansen, 1984), which we have previously shown to be a reliable measure of auditory selective attention across a wide age range, from adults to preschool children (Stevens, Lauinger, & Neville, 2009; Sanders, Stevens, Coch, & Neville, 2006; Coch et al., 2005). Participants were instructed to listen to one of two children's stories presented simultaneously in separate free-field speakers (Optimus Xts-10) situated 90° to the left and the right of the participant, placed 18 in. away from their chair on either side and approximately 9 in. below parallel with the ears. ERPs were recorded to 100 msec probe stimuli superimposed on the to-be-attended and unattended auditory channels. As reported in more detail elsewhere (Sanders et al., 2006), eight narratives ranging from 2.5 to 3.5 min in length were recorded and edited to remove pauses greater than 1 sec and to normalize the mean amplitude at about 60 dB SPL; the narratives consisted of a series of four related stories read by a male narrator and a separate series of four stories read by a female narrator. One story from each series was presented from the left and right speakers, with the two

audio channels always differing in narrator (male and female, respectively). Participants listened first to each of the four stories from one series and then listened to the four stories of the remaining series: half of the participants started with one series and half with the other. Direction of attention was counterbalanced with a pseudorandomized order (LRRL or RLLR), counterbalanced across participants and story series. Immediately after each story, participants were asked three comprehension questions to ensure they were attending to the appropriate narrative. No participant missed more than 1 question per story or 2 questions of 24 total, with accuracy near ceiling across all participants ($M = 97.3\%$, $SD = 0.66$).

Probe Stimuli

In both experiments, two types of auditory probe stimuli, linguistic and nonlinguistic, were superimposed on the stories in each audio channel. For Experiment 1, linguistic probes consisted of 100 msec recordings of the syllable /ba/ spoken by the male and female narrators; both types of probes were superimposed with equal probability on both the left and right spoken messages. Experiment 2 used a similar presentation technique, but with linguistic probes consisting of 100 msec segments of a synthetic digitized /ba/ with the pitch tuned to the fundamental frequency of the voice of the male narrator (164 Hz) and the female narrator (210 Hz). The nonlinguistic probe in both experiments was identical, consisting of a 100-msec noise burst created by scrambling the digitized /ba/ probe. All probes had an intensity of 74 dB SPL with 5 msec rise/fall times. In both experiments, the linguistic and nonlinguistic probes were presented in random order an equal number of times on both the attended and unattended channels (672 male /ba/ probes, 672 female /ba/ probes, 672 noise burst probes). ISI between probes was jittered to be short (175–225 msec), medium (475–525 msec), or long (975–1025 msec) in 1-msec steps for each length and evenly distributed across the three ISI lengths.

Visual WM Task

In Experiment 2, participants completed an additional behavioral task measuring WM capacity after the auditory selective attention task. The WM measure consisted of a well-studied change detection task (Luck & Vogel, 1997), which has been shown to produce reliable estimates of capacity that are not confounded by verbal processing, making these estimates robust with respect to individual differences in strategy (Vogel, Woodman, & Luck, 2001). Each trial began with a 150-msec sample array of 2, 4, or 8 isoluminant colored squares (black, blue, brown, cyan, green, orange, purple, red, white, or yellow) randomly distributed around a 14 in. × 10 in. video display. Participants were instructed to remember the location of each colored square during a retention interval of

1000 msec of a blank display. In the test array, one of the squares from the sample array appeared in either the same or a different color. For example, a yellow square in the upper left quadrant of the sample array could appear on the test array in the exact same spatial location either in yellow or one of the other nine colors, warranting a response of “same” or “change,” respectively. To emphasize accuracy over speed, the test array remained on the display until the participant responded. The task was broken into three blocks of 80 trials each, totaling 240 trials with 80 at each set size (2, 4, and 8), evenly divided between “same” and “change” trials. Individual estimates of visual WM capacity (k) were calculated for each participant using a standard formula (e.g., Cowan, 2001), where k = set size \times (hit rate – false alarm rate), averaged across all three set sizes (2, 4, and 8).

EEG Procedures

For the auditory selective-attention tasks in Experiments 1 and 2, EEG was recorded at a sampling rate of 512 Hz from 32 Ag/Ag-Cl-tipped scalp electrodes (BioSemi Active2, Amsterdam, Netherlands) arranged according to the international 10–20 system. Electrode offsets were maintained at ± 30 μ V or less throughout each recording session. Additional electrodes were placed on the outer canthus of each eye, below the right eye, and on the left and right mastoids. The EEG was recorded relative to the common mode sense active electrode and then re-referenced offline to the algebraic mean of the left and right mastoids. To monitor horizontal eye movement, the left and right outer canthus channels were re-referenced to one another, and to monitor vertical eye movement (and blinks), the lower right eye electrode was re-referenced to Fp1 (right anterior-most electrode). ERP analyses were carried out using EEGLAB (Delorme & Makeig, 2004). Raw EEG data were band-pass filtered from 0.1 to 40 Hz, then epochs time-locked to stimuli of interest were extracted from –100 to 500 msec relative to probe onset. Epochs containing large voltage deviations or muscle/movement artifacts were identified by visual inspection and excluded from further analysis. Remaining data were then submitted to the extended runica routine of EEGLAB. On the basis of scalp topographies and the component time series, ocular artifacts were identified and pruned from the data. Then, the pruned data were subjected to a more stringent, manual artifact rejection procedure, to remove any residual eye movement artifacts not removed completely by ICA. Statistical analyses were performed on mean amplitudes from averaged ERPs with factors of attention (attended vs. unattended side) and scalp distribution in a 2 (Left, Right Hemisphere) \times 2 (Lateral, Medial site) \times 6 (Frontal, Frontocentral, Central, Central-Parietal, Parietal, Parietal-Occipital) design. Electrodes included in the final analyses were F3/4, F7/8, FC5/6, FT7/8, C3/4, C5/6, T7/8, CP1/2, CP5/6, P3/4, P7/8, and PO3/4. Greenhouse–Geisser corrections are reported for factors with more than two levels.

ERP analyses were performed separately for linguistic (/baa/) and nonlinguistic (/bzz/) probe types. For linguistic probes, analyses were performed to test whether probe gender had differential effects on the early evoked response depending on whether the probe was presented with a narrator of the same gender (congruent linguistic probe) or a narrator of the opposite gender (incongruent linguistic probe). P1 mean amplitudes were analyzed 50–100 msec after the onset of congruent and incongruent linguistic probes in Experiments 1 and 2. In both experiments, there were no effects of congruency on P1 amplitude (Experiment 1, $F(1, 21) = .057, p = .813$; Experiment 2, $F(1, 21) = 1.109, p = .304$), nor interactions between congruency and attention (Experiment 1, $F(1, 21) = .402, p = .533$; Experiment 2, $F(1, 21) = .142, p = .710$). In view of the lack of narrator congruency effects on probe evoked responses, linguistic probes were collapsed across congruent and incongruent types for all analyses reported here.

RESULTS

Experiment 1

Attention Effects on ERPs

Figure 1 shows ERPs elicited by linguistic and nonlinguistic probes embedded in the dichotic listening task. ERPs to linguistic probes were characterized by P1 (50–100 msec) and N1 (100–150 msec) components followed by a sustained negativity, whereas ERPs to nonlinguistic probes featured a P1–N1 sequence followed by a broad P2 (150–250 msec). The waveform morphologies for both linguistic and nonlinguistic probes are consistent with those reported previously in adults (Sanders et al., 2006). To test whether attention was modulating the early P1 component to linguistic probes, the P1 peak was identified in the grand-averaged ERP across participants, and mean amplitudes were calculated over a 20-msec window centered on that peak for attended (82 msec) and unattended probes (86 msec) separately. For linguistic probes, there was a main effect of attention on P1 amplitude, $F(1, 21) = 16.14, p = .001$, with significantly larger amplitudes to attended probes relative to unattended probes. This effect was strongest at frontocentral electrodes sites [Attention \times Anteriority, $F(5, 105) = 4.37, p = .02$]. Subsequent to the P1, an enhanced negativity was elicited by attended linguistic probes over 150–200 msec at frontocentral electrodes [Attention \times Anteriority, $F(5, 105) = 7.228, p = .002$; Attention \times Laterality \times Anteriority, $F(5, 105) = 2.852, p = .038$].

In contrast, P1 amplitudes to the nonlinguistic probes, centered on the attended (82 msec) and unattended (86 msec) peaks, did not show an effect of attention, $F(1, 21) = 1.96, p = .18$, or a significant interaction between attention and scalp distribution factors (all $ps > .13$).¹ Nonlinguistic probes did show a robust later modulation by attention at the P2 component, which was quantified as the 20 msec

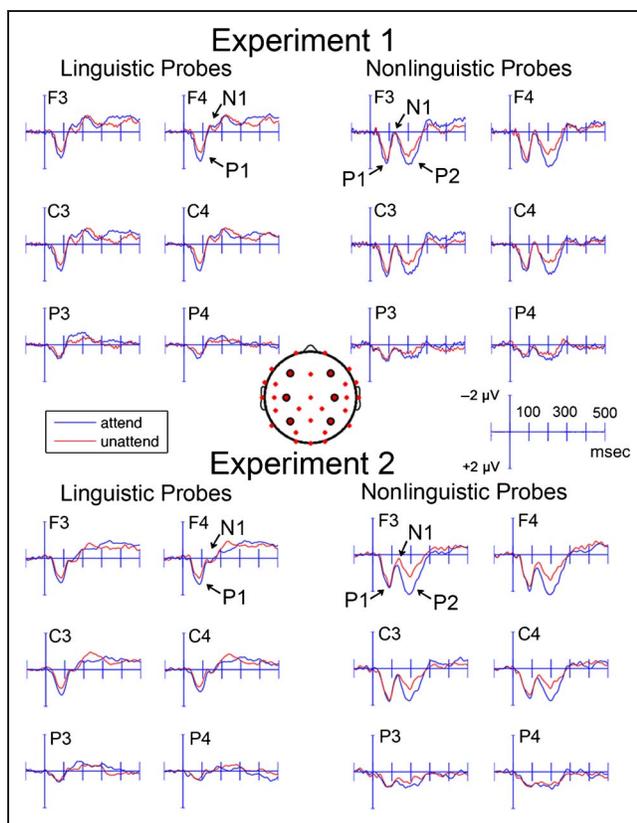


Figure 1. ERPs elicited by linguistic and nonlinguistic probes presented on attended and unattended auditory channels from Experiments 1 and 2. Electrodes shown are highlighted on the electrode montage depicted in the center of the figure. For both experiments, linguistic probes were characterized by a difference between attended and unattended probes at the P1 component, whereas nonlinguistic probes showed a later effect of attention on the P2 component.

window surrounding the P2 peak for attended (207 msec) and unattended probes (199 msec), $F(1, 21) = 10.30, p = .004$. As with the P1 attention effect for linguistic probes, this P2 enhancement for attended relative to unattended nonlinguistic probes was largest at frontocentral electrode sites [Attention \times Anteriority, $F(5, 105) = 4.85, p = .009$].

Because the P1 effect for linguistic probes occurred earlier than has been reported previously for auditory spatial attention in adults (i.e., Sanders et al., 2006), a second experiment was carried out to replicate the effect and to extend the findings. In particular, a separate visual WM capacity task was included to investigate whether individual differences in the amplitude of this early ERP attention effect might be associated with WM differences.

Experiment 2

Change Detection WM Task

The mean visual WM capacity estimate across all set sizes was 2.39 ($SD = 0.51$; range of 1.38–3.55). On the basis of these estimates, a median split was performed to divide participants into groups of high ($M = 2.87, SD = 0.37$)

and low WM capacity ($M = 1.91, SD = 0.28$) to make between-subject comparisons of ERPs from the auditory selective attention task.

Attention Effects on ERPs

As shown in Figure 1, the auditory ERPs elicited by linguistic and nonlinguistic probes embedded in the dichotic listening task in Experiment 2 were very similar to those elicited in Experiment 1 in a separate group of participants. However, as seen in Figures 2 and 3, these ERP attention effects differed as a function of WM capacity. Particularly for linguistic probes (Figure 2), the high WM capacity group showed an enhanced P1 amplitude to the attended-channel probes that was absent in the low capacity group, whereas the low capacity group showed a later attentional modulation resembling the “Nd” effect (Woods & Clayworth, 1987).

For linguistic probes, mean amplitudes in 20 msec windows centered on the P1 peak (82 msec, attended; 78 msec, unattended) revealed a significant Group \times Attention interaction, $F(1, 20) = 5.45, p = .030$, with the high capacity group showing an enhanced amplitude of the P1 evoked by attended relative to unattended probes ($p = .012$) that was absent in the low capacity group ($p = .59$). Furthermore, the magnitude of this P1 attention effect averaged across frontal, central, and parietal electrodes correlated significantly with individual estimates of visual WM capacity [$r(21) = .424, p = .025$, one-tailed]. As shown in Figure 2C, larger estimates of capacity were associated with a larger difference between attended and unattended P1 amplitudes to linguistic probes. Following the P1 attention effect in the high-capacity group was an effect with a similar topographic distribution over the interval 200–300 msec after probe onset (Figure 2B) [Group \times Attention, $F(1, 20) = 6.560, p = .019$; attended vs. unattended, high-capacity, $p = .006$; low-capacity, $p = .600$]. In contrast, the low capacity group showed a more sustained negativity (200–400 msec) in the attended relative to the unattended ERPs that reached significance at left medial electrode sites [Group \times Attention \times Hemisphere \times Laterality, $F(1, 20) = 6.560, p = .019$].

For nonlinguistic probes, statistical analyses of mean amplitudes in 20 msec windows centered on the P1 peak (82 msec, attended; 86 msec, unattended) confirmed that mean amplitudes of the P1 component were not significantly modulated by attention, $F(1, 20) = .941, p = .34$.² To assess the later P2 attention effect, mean amplitudes were calculated in 20 msec windows surrounding the peak of the P2 elicited by attended (195 msec) and unattended (195 msec) nonlinguistic probes, revealing a main effect of attention, $F(1, 20) = 7.342, p = .013$. As in Experiment 1, the P2 attention effect for nonlinguistic probes showed a frontocentral distribution [Attention \times Anteriority, $F(5, 100) = 9.571, p < .001$] similar to the distribution of the P1 attention effect observed for linguistic probes. Comparisons by group across all electrodes

showed that the P2 attention effect was significant in the high-capacity group [omnibus attended vs. unattended, $p = .013$] but not in the low capacity group [$p = .283$], whereas both groups showed pronounced effects of attention at regions of the scalp where the P2 was maximal [Attention \times Hemisphere \times Anteriority, $F(5, 100) = 2.886$, $p = .027$; Attention \times Laterality \times Anteriority, $F(5, 100) = 4.263$, $p = .005$]. Figure 3C shows that the magnitude of the P2 attention effect for nonlinguistic probes was not significantly correlated with individual differences in WM capacity [$r(21) = .130$, $p = .282$, one-tailed].

DISCUSSION

The current study examined individual differences in visual WM capacity and auditory selective attention, as a test of the hypothesis that differences in domain-general attentional control might underlie variation in online WM capacity. The first experiment demonstrated a previously unreported early modulation by attention of the auditory P1 component (~ 80 – 90 msec) elicited by linguistic probe sounds sharing features with attended speech passages. In a

second experiment, we replicated this finding of an early attentional modulation of the auditory P1 to linguistic probes and further showed that this early attention effect was correlated with performance on a separate measure of visual WM capacity. Overall, these findings parallel the relationship between WM capacity and attentional control that has previously been demonstrated within the visual modality (e.g., Fukuda & Vogel, 2009, 2011) and extend the scope of that relationship to include auditory attentional control.

In general, the earliest component of the human auditory ERP that is consistently modulated by selective attention in adults is the N1 at 80–140 msec (for reviews, see Herrmann & Knight, 2001; Giard, Fort, Mouchetant-Rostaing, & Pernier, 2000; Hillyard, Mangun, Woldorff, & Luck, 1995), although there is evidence of an earlier P20–50 modulation in studies where auditory attention was highly focused on rapidly presented tone pips (Woldorff & Hillyard, 1991; Woldorff, Hansen, & Hillyard, 1987) and during intermodal selective attention (Karns & Knight, 2009; Hackley, Woldorff, & Hillyard, 2007). Here, employing dichotic presentations to emphasize early selection using naturalistic language

Figure 2. (A) ERPs elicited by attended and unattended linguistic probes during Experiment 2 for high- and low-capacity groups. (B) Topographic maps of the difference between attended and unattended mean amplitudes elicited by linguistic probes, separately for high- and low-capacity groups. (C) Correlation between the P1 attention effect (attended minus unattended amplitudes) and individual performance on the visual change detection WM task. Mean amplitudes of the P1 to attended and unattended probes were extracted in 20 msec windows centered on the respective P1 peaks.

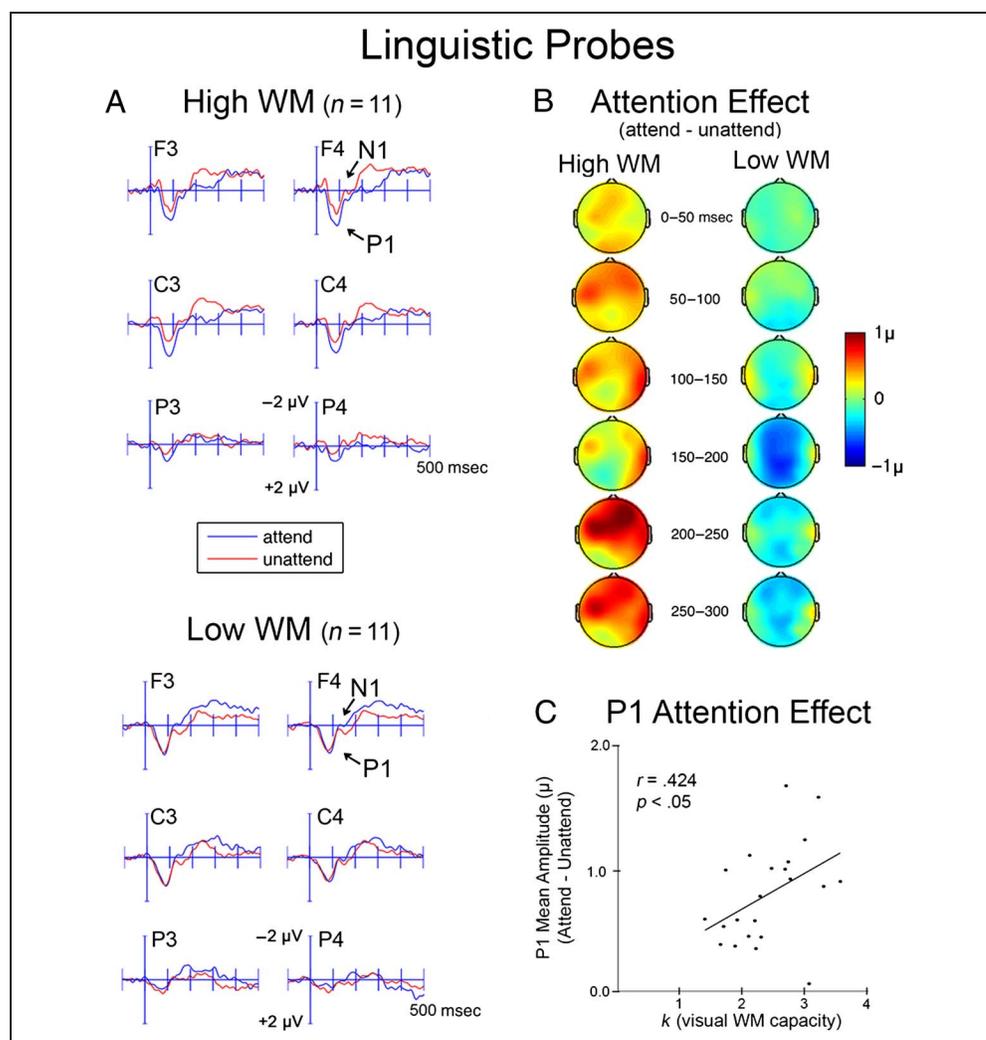
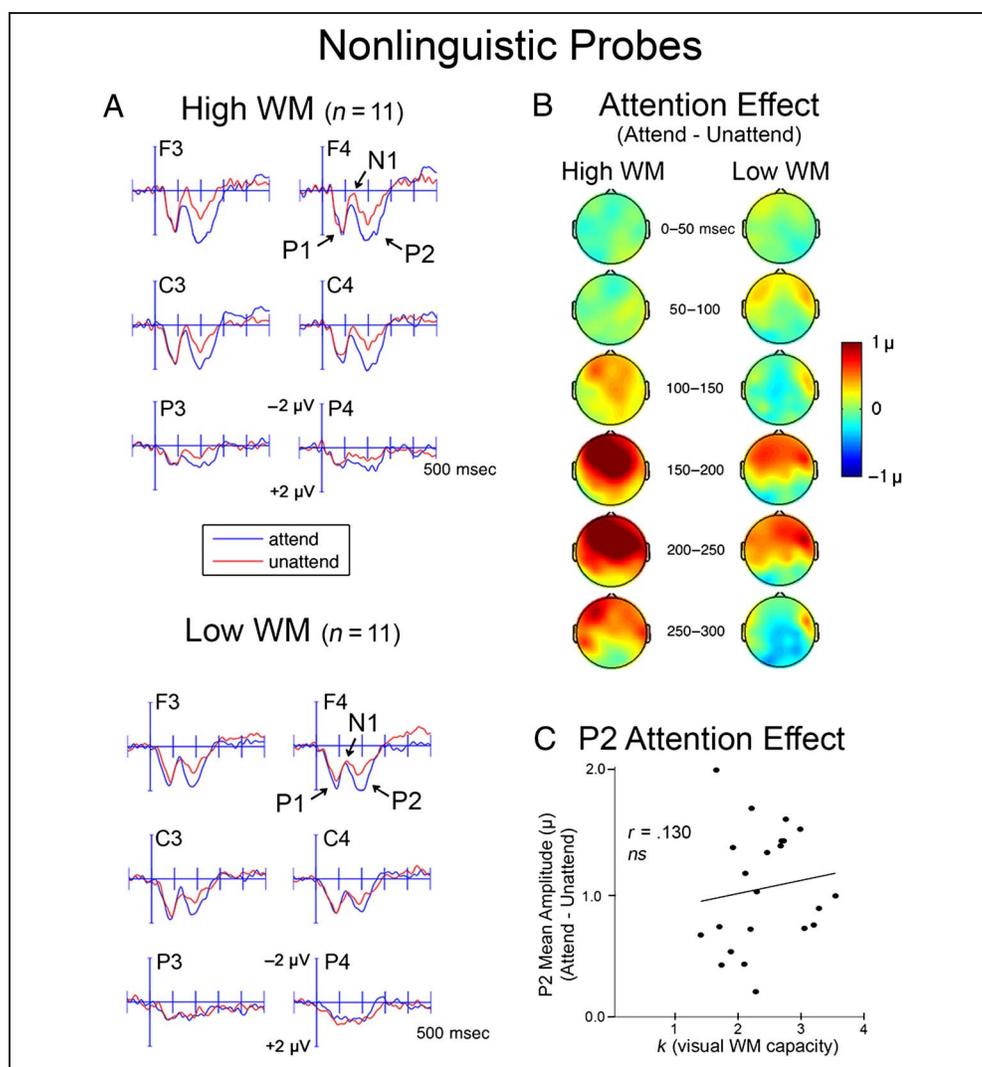


Figure 3. (A) ERPs elicited by attended and unattended nonlinguistic probes during Experiment 2 for high- and low-capacity groups. (B) Topographic maps of the difference between attended and unattended mean amplitudes elicited by nonlinguistic probes, separately for high- and low-capacity groups. (C) Correlation between the P2 attention effect and individual performances on the visual change detection WM task. Mean amplitudes of the P2 to attended and unattended probes were extracted in 20 msec windows centered on the respective P2 peaks.



stimuli, we report a robust effect of attention on the first major positive peak (P1) in the auditory evoked potential at around 80–90 msec. This effect may be comparable to findings that visual spatial attention enhances the visual-evoked P1 amplitude, which appears to reflect facilitated sensory processing for stimuli presented at a location where attention is currently focused (Hopfinger, Luck, & Hillyard, 2004; Hillyard & Anillo-Vento, 1998; Luck, Heinze, Mangun, & Hillyard, 1990). Consistent with the enhanced sensory processing view of the P1, Giuliano, Pfordresher, Stanley, Narayana, and Wicha (2011) reported an enhanced auditory P1 in tone language speakers to pitch changes during an auditory change detection task, which the authors interpreted as facilitated processing of pitch information because of native experience using pitch contours in language production and comprehension.

In the current experiments, the modulation of P1 amplitude by attention was only reliable for linguistic probes. This is likely a consequence of the linguistic probes sharing more perceptual features with the spoken narratives than the nonlinguistic probes. Because the linguistic probes

thus blended into the attended and unattended speech passages, they would be more subject to modulation by selective attention mechanisms directed toward the acoustic features of the ongoing speech (enhancing the attended and/or suppressing the unattended passage). Consistent with this idea, the large P1 amplitudes elicited by nonlinguistic probes at attended and unattended locations suggests that these probes had a high degree of feature mismatch with both narratives, eliciting a similar level of early sensory processing of probes at both locations. However, this apparent dissociation between linguistic and nonlinguistic probes may be a matter of degree, because there was a less reliable but possibly significant P1 attention effect for nonlinguistic probes (see footnotes 1 and 2).

The finding of larger P1 attention effects in individuals with greater visual WM capacity suggests that domain-general attention systems are implicated in processes of WM. On the basis of previous studies that ascribed such early auditory attention effects to sensory gating (Woldorff & Hillyard, 1991), the P1 attention effect observed here is likely because of spatial attention biasing sensory processing

toward inputs presented at an attended spatial location (e.g., Hillyard et al., 1995). The positive correlation of this P1 effect with increased WM capacity is thus consistent with the hypothesis that higher capacity individuals exercise better control of their “attentional spotlight” (Fukuda & Vogel, 2009); in particular, it appears that high capacity individuals can maintain their attentional focus more effectively on an attended channel than low capacity individuals, who are more likely to have their attention captured by distracting information in an unattended channel.

In contrast to previous reports, the attentional modulations observed here did not show the robust N1 effect demonstrated in similar auditory selective attention studies (Sanders et al., 2006; Coch et al., 2005; Woods et al., 1984; Hink & Hillyard, 1976). However, our results are similar to those of Sanders et al. (2006), who used a nearly identical experimental procedure and found an emerging but nonsignificant P1 attention effect followed by a sustained N1 effect resembling the Nd component. In Experiment 2, we showed that this early P1 attention effect was characteristic of a group of high WM participants, whereas the later, sustained Nd-like effect was characteristic of a low WM group, suggesting that there is variability in the morphology of attention effects that can be accounted for by WM ability. It should be noted that the timing of the P1 attention effect (80–90 msec) reported here is similar to the “Nd80” component reported by Woldorff and Hillyard (1991) as the first phase (60–100 msec) of the N1 attention effect. Furthermore, magnetoencephalographic studies of auditory selective attention have reported that the magnetic counterparts of the P1 and N1 components (M50 and M100, respectively) both emerge from similar sources on the supratemporal plane near Heschl’s gyrus (Weisser et al., 2001; Woldorff et al., 1993). Taken together, the auditory P1 and N1 components may reflect a common sensory gating mechanism that is implicated in the early selection of information as it reaches the primary auditory cortex, perhaps operating as an early gain-control mechanism.

In contrast to the variability in P1–N1 results, the P2 attention effect observed here for nonlinguistic auditory probes is consistent with the P2 attention modulations observed specifically for nonlinguistic sounds in previous experiments testing selective attention for language stimuli (Sanders et al., 2006; Coch et al., 2005; Woods et al., 1984). Considering that attentional modulation of this component was not related to individual differences in WM capacity in Experiment 2, the consistency of the auditory P2 attention effect across contexts seems to reflect an attentional mechanism that is less related to the selection of task-relevant information. This is in agreement with previous reports of the P2 as an “obligatory cortical potential” with little variability across individuals (see review by Key, Dove, & Maguire, 2005). Interestingly, magnetoencephalographic studies have localized the auditory P2 to a source near the superior temporal plane overlapping with a previously reported source of the P3a component (Hegerl & Frodl-Bauch, 1997), which has been implicated

in involuntary attention to novel stimuli (Knight, 1996; Squires, Squires, & Hillyard, 1975). Thus, the auditory P2 attention modulation may be akin to the P3a effect.

To our knowledge, the present results offer the first evidence that individual differences in WM capacity per se can predict attention performance in a separate sensory modality. Previous studies demonstrating a relationship between auditory attention and WM capacity have employed complex span measures of capacity (Sörqvist et al., 2012; Tsuchida et al., 2012; Colflesh & Conway, 2007; Conway et al., 2001), which tap memory retrieval skills in addition to capacity (Unsworth & Engle, 2007b). Here, we employed a measure of WM that was previously shown to be robust to individual differences in strategy use (Vogel et al., 2001) and highly predictive of the degree of focus of an individual’s “spotlight” of visual spatial attention (Fukuda & Vogel, 2009, 2011) as well as performance on standard measures of fluid intelligence (Fukuda, Vogel, Mayr, & Awh, 2010). The present results broaden the scope of these findings, suggesting that the predictive power of WM capacity for measures of fluid intelligence and scholastic achievement stems from an underlying attentional control process that is shared across sensory modalities. Given that most measures of fluid intelligence (e.g., Raven’s Progressive Matrices, Cattell’s Culture Fair Test) and scholastic achievement (i.e., standardized tests) are primarily visual tasks, future research should directly test whether domain-general attention control mechanisms are as predictive of performance on such aptitude tests as has been shown with visual measures (Fukuda et al., 2010).

In summary, the observed relationship between early modulation of auditory attention and individual estimates of visual WM capacity reported here provides strong evidence for the hypothesis that domain-general attentional resources underlie individual differences in WM capacity (e.g., Cowan et al., 2005). We conclude that the amount of visual information an individual can hold in WM predicts how well that individual can focus their attention in auditory space, thereby implicating the existence of a supramodal attention network that controls the flow of information into WM.

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Notes

1. It should be noted that post hoc analyses of the nonlinguistic P1 effect suggested these trending p values were driven by the presence of a significant P1 attention effect at specific frontocentral electrodes (attended vs. unattended, FC5, $p = .014$; C5, $p = .024$).

2. There was a significant interaction between attention and scalp distribution factors; however, this appeared to be because of the frontocentral distribution of the P1 being more pronounced in the attended than unattended conditions [Attention \times Anteriority, $F(5, 100) = 3.594, p = .025$]; within this interaction, post hoc comparisons revealed a trending effect of attention at frontal ($p = .063$) and frontocentral electrodes ($p = .058$).

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