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The Electrophysiological Time Course of the Interaction of Stimulus Conflict and the Multisensory Spread of Attention

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Abstract

Previously, we have shown that spatial attention to a visual stimulus can spread across both space and modality to a synchronously presented but task-irrelevant sound arising from a different location, reflected by a late-onsetting, sustained, negative-polarity event-related potential (ERP) wave over fronto-central scalp sites, likely originating in part from the auditory cortices. Here we explore the influence of cross-modal conflict on the amplitude and temporal dynamics of this multisensory spreading-of-attention activity. Subjects attended selectively to one of two concurrently presented lateral visual-letter streams to perform a sequential comparison task, while ignoring task-irrelevant, centrally presented spoken letters that could occur synchronously with either the attended or unattended lateral visual letters and could be either congruent or incongruent with them. Extracted auditory ERPs revealed that, collapsed across congruency, attentional spreading across modalities started around 220 ms, replicating our earlier findings. The interaction between attentional spreading and conflict occurred beginning at around 300 ms, with attentional-spreading activity being larger for incongruent trials. Thus, the increased processing of an incongruent, task-irrelevant sound in a multisensory stimulation appear to occur some time after attention has spread from the attended visual part to the ignored auditory part, presumably reflecting that the conflict detection and associated attentional capture occurs after the accrual of some multisensory interaction processes at a higher-level semantic processing stage.

Keywords

auditory; visual; EEG; ERP

Introduction

While driving a car, maintaining visual attention on the surrounding traffic is essential, and ignoring irrelevant auditory distraction generally beneficial. However, even though ignoring irrelevant, distracting conversation from a passenger might improve the effectiveness of our driving, ignoring his/her warning about an upcoming, potentially dangerous event could be quite disadvantageous. Evolutionarily speaking, it seems beneficial that our brains are capable of parsing and assessing conflicting, possibly relevant, information from concurrently occurring input.

Recently, we showed that attention can spread from an attended visual stimulus to a task-irrelevant, simultaneously presented, auditory stimulus, even when the two arise from different spatial locations (Busse et al., 2005). The spreading of attention was manifested as a late-onsetting (220ms), sustained, frontally distributed, event-related potential (ERP) wave elicited by auditory stimuli that occurred synchronously with an attended visual stimulus, relative to when they occurred with an unattended one. In that study, however, the effects were observed using very simple visual and auditory stimuli with no apparent higher-level representation-related congruence or incongruence.

The way the brain responds to conflicting stimulus input has been studied extensively using classic paradigms such as the Stroop (Stroop, 1935) and flanker paradigms (Eriksen & Eriksen, 1974). These studies have typically observed an increased negative-polarity ERP wave to incongruent (i.e., conflicting) versus congruent stimulus input over fronto-central scalp sites peaking 250-400ms poststimulus (e.g., Wendt et al., 2007; Bartholow et al., 2005; West and Alain, 1999; Yeung et al., 2004; Appelbaum et al., 2009), an electrophysiological response thought to arise in part from increased activity in the anterior cingulate cortex (Van Veen and Carter, 2002; Fan et al., 2003, 2007; Hanslmayr et al., 2008). Most such stimulus-conflict studies, however, have been carried out within a single modality. Moreover, studies that have investigated cross-modal conflict have typically had the auditory and visual sensory components occurring at the same location (e.g., Fiebelkorn et al., 2010; van Atteveldt et al., 2007). Thus, it is not at all clear how the spreading of attention across the spatially separated sensory components of a multisensory stimulus might vary as a function of whether, and how, those components conflict.

Here, we used the high temporal resolution of event-related-potential (ERP) recordings to examine the influence of cross-modal conflict on the amplitude and timing of multisensory spreading-of-attention activity. We presented letter-sound combinations while subjects selectively attended to one of two lateralized visual letter-streams and ignored task-irrelevant, centrally presented, spoken letters that could occur synchronously with either the attended or unattended lateral visual letters and could be either congruent or incongruent with them. We hypothesized, first of all, that spreading-of-attention activity would likely differ in amplitude as a function of cross-modal incongruence, either being smaller due to suppression of the conflicting auditory input or larger due to increased attentional capture by the conflicting input. Secondly, the influence of cross-modal incongruence might occur in close temporal conjunction with the attentional spreading, onsetting at the same time, or it could be contingent upon the accrual of some attentional spreading and multisensory interaction processes, thus onsetting sometime after.

Material and Methods

Participants

Twenty-six healthy, right-handed participants (aged 18–35 years; equal numbers of males and females) participated in the experiment. Ten of these participants were excluded in the final data analysis because more than 50% of their trials had to be rejected due to eye-movement artifacts. All 26 participants gave written informed consent after receiving an explanation of the procedures, using a protocol approved by the Duke University Institutional Review Board. Participants were paid \$15 per hour for their participation.

Paradigm

The study incorporated a variation of the classic “1-back” paradigm, consisting of a stream of compound trials made up of sequential pairs of visual letters (“A”, “X” or “H”) that could be either identical or different and could be accompanied by a task-irrelevant,

simultaneously presented, spoken letter of similar or different identity. All visual stimuli in these compound trials were presented randomly from a left or right lower-visual-field location, whereas the occasionally accompanying auditory stimulus was always presented from a central position (see Fig.1).

For each run, participants were instructed to covertly attend to one of the two visual streams (left or right location) and to ignore both the visual stimuli on the other side and all of the centrally presented spoken letters sounds. Visual stimuli consisted of sequentially presented letter stimuli at one of the two (attended or unattended) lower visual field locations; pairs of letters were usually identical (“matched”) but sometimes were not. At the attended location only, nonidentical pairs required responses of the subjects (i.e. these were thus *target* pairs). More specifically, subjects were instructed to press one of two buttons with their right index finger when the second letter of a covertly attended visual pair sequence was an “A” (and was thus preceded by an “X”), and press the other button when it was an “X” (and thus was preceded by an “A”).

Two-thirds of the letters of each of the lateralized visual letterstreams consisted of possible task-relevant (when in the attended stream) sequential letter pairs (X and/or A) and one-third were task-irrelevant pairs [H and/or no letter (“no-stim”)], the latter serving to separate the task-relevant sequential pairs when they appeared in immediate succession within the same stream. These irrelevant pairs that served as separators, consisted of either two “H”s in a row, two null events (“no-stims”) in a row, or an “H” followed by a null event or vice versa, in equal proportion.

In the task-relevant sequential pairs (attended or unattended), 34% of the trials were visual-only-trials (pure lateralized visual letters, no accompanying sound) and 66% were multisensory (lateralized visual letters accompanied by a synchronous, centrally presented, spoken letter “A” or “X”, male voice), which could be either congruent (50%) or incongruent (50%) with the corresponding lateralized visual letter in that trial. These task-relevant trials could contain the following types of sequential pairs: X-followed-by-X, A-followed-by-A, A-followed-by-X and X-followed-by-A. In these trials, 78% of the pairs included visual sequentially matching letters (“AA” or “XX”), which could be either “AA” (50%) or “XX” (50%). The remaining 22% of these trials consisted of visual sequentially non-matching letters (“AX” or “XA”), which were the target sequence pairs to detect. These occurred with equal probability (50% “AX” and 50% “XA” pairs).

The sequential pairs of visual-letter stimuli were presented in random order to the left and right side. In addition, whether the individual lateral visual stimulus pairs were accompanied by task-irrelevant central auditory letters was also randomized, such that the order of presentation of the multisensory context (pure [visual alone], congruent multisensory, or incongruent multisensory) was unpredictable. All stimuli (both visual and auditory) were presented for a duration of 250 ms. The stimulus-onset-asynchrony (SOA) between the two stimuli of a sequential pair as well as between two sequential pairs was 625 ms.

The visual letters were presented 9.5 degrees to the left or right of the fixation cross, and vertically 4 degrees below fixation. They were presented in two rectangular boxes (size $3.8 \times 5 \text{ cm}^2$), which remained on the screen continuously during the entire runtime, serving as attentional anchors to assist the participant in maintaining a strong covert attentional focus at the spatial position of the to-be-attended visual letter stream.

All participants completed 14 runs, seven in which they attended covertly to the right lateral stream, and seven in which they covertly attended to the left one (in randomized order). Each run lasted about 3.5 min, leading to a total experimental runtime of about 47 min.

EEG Recording

The EEG was recorded from 128 channels mounted in a customized elastic electrode-cap (Duke128 Waveguard cap layout, made by Advanced Neuro Technology [ANT], the Netherlands), referenced to the average of all channels during recording. The 128 channels were equally spaced across the cap and covered the whole head from above the eyebrows to lower aspects of the occipital cortex (slightly past theinion). Electrode impedances were kept below 5k Ω for all 128 electrodes. The ground electrode was placed on the collar bone. Horizontal eye movements were detected by two extra bipolar electrodes placed at the outer canthi of the eyes, whereas vertical eye movements or blinks were detected by another pair of bipolar electrodes, placed below and above the right eye. All EEG and EOG channels were recorded continuously in DC mode from a 128-channel, high-impedance ANT-Waveguard amplifier with active cable-shielding technology, which were digitized with a sampling rate of 512 Hz per channel for offline storage and analysis. Recording was done in a sound-attenuated, electrically shielded chamber, kept in relatively low lighting.

After the end of the 14 experimental runs, the locations of the electrodes were digitized for each participant using a 3D spatial digitizer (Polhemus, Inc., USA). These locations were used later to more accurately calculate topographic distributions of the grand-average ERP waveforms based on the mean of all included participants electrode locations (standard error of these locations across subjects and electrodes: x-axis: ± 1.16 mm; y-axis: ± 1.34 mm; z-axis: ± 2.14 mm).

Data Analysis

Behavioral Data—The behavioral responses to the target stimuli (i.e., the second stimulus in sequentially presented pairs of non-matching visual letters) were analyzed primarily to estimate the behavioral influence of conflicting sounds during visual stimulation (e.g., van Atteveldt et al., 2007). Only trials for which the behavioral responses occurred between 200–1000 ms after the second letter of a sequential target pair were considered for further behavioral analysis. Reaction times (RTs) and accuracy for correctly detected sequential letter pair orders were computed separately for the congruent, incongruent, and pure-visual conditions. Repeated-measures analyses of variance (ANOVAs) were performed, using the within-subject factor CONDITION (congruent/incongruent/pure) to check for significant differences between conditions. Significance was inferred for Greenhouse-Geisser corrected *p*-values lower than 0.05.

EEG Data—Data were preprocessed with the commercial software package ASA (Advanced Neuro Technology) and then analyzed further using custom ERPSS software (UCSD, San Diego, CA). Preprocessing included high-pass filtering of the data (Butterworth Filter, cut-off frequency 0.016 Hz, linear roll-off 12 dB/oct) to exclude ultraslow DC-drifts, prior to transformation of the data into ERPSS format for further analysis.

We confined our EEG-analyses to the first letter of the sequential pair, as these trials were not contaminated by button-press-related or target-detection-related processes. The continuous EEG data were divided into 800 ms epochs, time-locked to the first letter in the various pairs and included a prestimulus baseline of 200 ms. Artifact rejection was performed off-line by discarding epochs contaminated by eye movements, eye blinks, excessive muscle activity, drifts, or amplifier blocking. Non-artifact EEG epochs were then averaged together, separately for the various trial types. These averages were then subsequently digitally low-pass filtered with a running-average filter of 9 points (which at our sampling rate of 512 Hz corresponds to a low-pass filter cutoff of approximately 57 Hz) and re-referenced to the algebraic mean of the two mastoid electrodes. For the testing of multisensory spreading of neural activity, we used a frontal-central region of interest (ROI)

that matched as closely as possible the four electrode positions where visual attention spreading was reported in Busse et al. (2005) (i.e., approximately Fz, FCz, FC1 & FC2 in the standard 10-20 system, corresponding in our system to channels Z4, Z5, L4, and R4). To test for significant effects of the various conditions, statistical analyses were computed in successive time bins of 20 ms of averaged data, between 0 ms and 600 ms.

Check for effective covert visual spatial attention—To check whether the participants successfully maintained selectively directed covert attention to the designated letter stream, we examined the amplitude of the visual N1 component of the visual-only trials as a function of whether they were attended versus unattended. The visual N1 component was measured over a left and a right parietal-occipital ROI, averaged across four electrode sites on each side, (centered approximately over the standard 10-20 sites P3/PO5 on the left and P4/PO6 on the right; see Fig. 2). Repeated-measures ANOVAs were used to test for visual spatial attention effects by testing for significance of the 3-way interaction between the factors ATTENTION (attended/unattended), STIMULUS-LOCATION (left/right) and HEMISPHERE (left/right).

Multisensory spreading of attention—To examine the spreading of attention towards the synchronously occurring auditory input (cf. Busse et al., 2005), we used a series of subtractions to extract the ERP response to the task-irrelevant, centrally presented auditory stimulus (i.e., the spoken letter) as a function of its multisensory context. In a first step, we extracted the auditory ERP when the sound occurred synchronously with an attended versus an unattended lateral visual letter, collapsed over incongruent and congruent stimulus types, thereby revealing the main effect across time of the multisensory spreading of attention. (See Results and Figure 3 for details on this extraction process). In a second series of steps, the attentional-spread ERP waveforms were extracted separately for incongruent and congruent multisensory combinations, and contrasted in multiple ways to assess the influence of cross-modal stimulus conflict on the spreading of attention activity.

Results

Behavioral Results

For the attended sequential pairs of visual letters “A” and “X” that did not match (i.e. the target sequential pairs), subjects responded with a button press after the second item in the pair, reporting whether it was an “A” or an “X”. Correct responses were defined as behavioral responses occurring between 200-1000 ms following the onset of the second letter of the sequential pair. The overall accuracy of the subjects collapsed across the multisensory context conditions was relatively high, averaging 91%, which did not differ significantly as a function of condition. The mean response times (RT) collapsed across the multisensory context conditions was 672 ms, which *did* vary as a function of condition, as described below.

Grand-average ($n=16$) mean response times, averaged over the responses to visual letters “A” and “X”, were 669 ms (standard deviation [SD] 157 ms) for the pure (unisensory) visual stimuli, and 648 ms (SD 162 ms) and 700 ms (SD 177 ms) for the multisensory congruent and incongruent audio-visual stimuli, respectively. A repeated-measures ANOVA including the factor CONDITION with 3 levels (pure, con, inc) revealed a highly significant effect of multisensory context ($F(1.45,22.45) = 16.6, p < 0.0001$, Greenhouse-Geisser corrected). Specific comparison tests indicated that RTs to the incongruent multisensory targets were significantly slower than to the congruent ones ($F(1,15) = 55.5, p < 0.0001$). Additional specific comparisons also indicated that RTs to pure visual targets were significantly faster than incongruent visual target responses ($F(1,15) = 7.9, p = 0.013$), but

were significantly slower than congruent responses ($F(1,15) = 5.7, p = 0.03$), suggesting that there was no general arousal effect of the sound on the visual letters over the multisensory conditions. These behavioral results indicate that, while attending the laterally presented visual letters, subjects appeared to be influenced by the presence of the centrally presented, task-irrelevant incongruent sounds, being distracted (slower) when they were incongruent and facilitated when they were congruent.

EEG Results

Evidence of covert visual spatial attention—Indication of selectively focused covert spatial attention on the designated lateralized letter stream was explored by examining visual spatial attention effects on the amplitudes of the parietal-occipital sensory N1 component for the pure visual stimuli, contralateral to the direction of attention. Visual spatial attention effects on the N1 amplitude are shown in Figure 2, for the left and right parietal-occipital ROIs. Repeated-measures ANOVAs confirmed the presence of robust visual spatial attention effects by a significant 3-way interaction between the factors ATTENTION (attended/unattended), STIMULUS-LOCATION (left/right) and HEMISPHERE (left/right) ($F(1,15) = 5.3, p = 0.004$), resulting from the N1 being larger for the visually attended visual letter stimuli. These robust visual attention effects indicate that our participants performed the attentional task as instructed.

Multisensory spreading of attention averaged across congruency conditions

—We first extracted auditory ERP activity independent of multisensory context (i.e. averaged across congruent and incongruent trial types) by subtracting activity elicited by attended visual-only (V) trials from activity elicited by the attended multisensory (AV) trials (see Fig.3, left side for the electrode site Z4 [$\sim$ Fz]). The analogous subtraction was also applied to the unattended trial responses (Fig.3, right side). This subtraction removes the simple visual sensory components and visual attention effects that are in common to the pure visual stimuli and the visual part of the multisensory stimuli. In a second subtraction step, these data were used to compute attended-context minus unattended-context ERP difference wave (Fig. 3 bottom), which isolates activity specific for the ‘spreading-of-attention’ across the component parts of a multisensory object (cf. Busse et al., 2005).

This activity specific for the ‘spreading-of-attention’ over sound and space appeared as a late-onsetting (220 ms), long-lasting, frontally distributed negativity (see traces over the fronto-central ROI in Fig. 4A and scalp-potential distribution maps in Fig. 4C). Within-subjects repeated-measures ANOVAs, including the factor ATTENTION (attended visual vs. unattended visual) revealed that extracted auditory ERPs were significantly more negative over fronto-central scalp sites for spoken letters occurring synchronously with an attended visual event than with an unattended visual event, starting at 220 ms ($F(1,15) = 17.6, p < 0.0008$ between 220-240 ms) and ending at 480 ms post-stimulus onset, with $F(1,15)$ values ranging between 17.6 and 6.3, and corresponding p -values between 0.0008 and 0.025).

Multisensory attentional spread as a function of congruency—Our main goal in the present study was to examine interaction effects of higher-level representation-related stimulus conflict on the multisensory spreading of attention. In the paragraphs below, we first discuss attentional-spread ERP activity across time separately for the incongruent and congruent multisensory conditions. Then we discuss the interaction effects between the two multisensory context conditions.

Specific analyses for the congruent stimuli (Fig.5A & 6A) showed significant spreading of attention activity over the frontal-central ROI (as revealed by a significant increased

negativity for the attended, compared to the unattended condition), but occurring in two, somewhat separated, time ranges. The first time range started at 220 ms and persisted until 300 ms. Tested within 20 ms windows of averaged data over the frontal-central ROI, main effects of multisensory attentional context were found with $F(1,15)$ values ranging between 18.7 and 6.6 (corresponding p -values between 0.0006 and 0.022). The second time period started at 340 ms and persisted until 440 ms (main effects of multisensory attentional context: $F(1,15)$ values ranging between 7.6 and 4.7, corresponding p -values between 0.015 and 0.05).

For the incongruent stimuli (Fig. 5B & 6B), within-subject repeated measures ANOVAs, including the factor ATTENTION (attended-visual/unattended-visual) and applied to the frontal-central ROI, revealed a significant difference in the frontal negativity between the attended-visual and unattended-visual visual conditions (i.e., the attentional spreading activity) starting at around 220 ms and persisting continuously until 500 ms (main effects of multisensory attentional context: $F(1,15)$ values ranging between 37.4 and 5.9, corresponding p -values between 0.0001 and 0.03 for the 20-ms windows). No significant effects were found between 500 and 540 ms, but significant differences reoccurred between 540 and 600 ms ($F(1,15)$ values ranging between 8.5 and 11.2, corresponding p values between 0.004 and 0.015).

In order to reveal interaction effects of attention and conflict, we computed the “spreading of attention” ERP activity (attended versus unattended extracted auditory ERPs) separately for the incongruent and the congruent trial types (double difference waves in Fig. 4C & 5C), and compared these. This contrast indicated that the spreading-of-attention negativity was *larger* for incongruent than for congruent multisensory stimuli over fronto-central scalp sites (Fig. 5C & 6C). The corresponding within-subject repeated measures, applied to data from the frontal-central ROI, revealed a significant interaction between ATTENTION (attended-visual / unattended-visual) and CONGRUENCY started at 300 ms and persisted until 360 ms ($F(1,15)$ values ranging between 7.0 and 6.0, corresponding p values between 0.02 and 0.03 across 20 ms windows), with a trend towards significance between 360–380 ms ($F(1,15) = 4.0$, $p = 0.065$). After this initial phase, the interaction effect reappeared for a short time period between 540 and 560 ms ($F(1,15) = 5.0$, $p = 0.04$). Thus, attention drawn towards the auditory part of the multisensory object appeared to be larger during processing of conflicting, non-matching letter-sound combinations, compared to matching ones.

The effect of incongruency as a function of multisensory attentional context—

As another way of examining the interaction between attentional context and conflict-related activity, we examined the effects of the incongruency of the task-irrelevant auditory stimuli as a function of the multisensory attentional context (see Fig. 7A&C). As can be seen from the figure, a conflict effect (incongruent minus congruent stimuli) was only present in the attended-visual condition, and not in the unattended-visual one. This observation was confirmed by specific comparisons showing significant conflict activity over the frontal-central ROI when the visual stimulus was attended (as revealed by a significant increased negativity for the incongruent, compared to the congruent condition), which was manifested in two, separated, time ranges (220–380 ms) and (520–600 ms, $p < 0.034$) (p 's between .05 and .001, analyzed in 20-ms bins). In contrast, there were no significant differences for the analogous comparisons for the visual-unattended conditions. Thus, conflict processing for the task-irrelevant auditory stimuli occurred when the simultaneous visual stimulus was attended, and not when it was unattended.

Discussion

In the present study, we investigated the amplitude and temporal characteristics of the 'spreading-of-attention' across a multisensory audiovisual object when the auditory and visual stimulus components were not only spatially discordant, but also conflicted at a semantic or representational level. To examine the spreading of attention towards the synchronously occurring auditory input (cf. Busse et al., 2005), we extracted auditory ERP waves by subtracting visual activity (V) from multisensory (AV) activity, separately for the attended-visual and unattended-visual conditions, which could then be compared. First, collapsed across visual-auditory congruency conditions, these activation patterns replicated our previously reported results from Busse et al. (2005), which had shown a spread of attention from the visual towards the auditory part of a multisensory stimulus that was comprised of spatially discordant, but simple, auditory and visual stimulus components. Secondly, the spreading of attention in the present study occurred for both the congruent and incongruent conditions, starting at the same point in time (220 ms). Third, interactions of this spreading of attention activity and multisensory conflict at a higher representational-level began at a later point in time, starting at around 300 ms, expressed in the form of increased activity for the incongruent compared to congruent stimulus combinations. Moreover, specific comparisons analyzing this interaction indicated that the visual-auditory conflict effects were only significantly present when the laterally presented visual component was attended, being absent when it was unattended. These findings suggest that as attention spread across both modality and space to the centrally presented, task-irrelevant, auditory stimuli, these auditory stimuli tended to attract even greater attention when they were incongruent with the task-relevant attended visual stimulus. Furthermore, these incongruency effects interacting with attention spreading occurred some time after attention had begun to spread from the visual to auditory stimulus part, suggesting that the higher-level conflict is detected after the accrual of some multisensory interaction processes at a semantic or representational level.

Multisensory Spread of Attentional Collapsed Over Congruency Relationships

Collapsed over incongruent and congruent multisensory trial types, the extracted auditory ERPs showed attentional spreading activity starting at ~220 ms, reflected as an enhanced, sustained, negative wave over fronto-central scalp for the task-irrelevant central spoken sounds when they occurred simultaneously with an attended versus an unattended lateral visual-letter stimulus. This effect was very similar to the effect reported over comparable scalp sites by Busse et al. (2005), in which the task-relevant lateral visual stimuli were simple geometric figures and the task-irrelevant centrally presented auditory stimuli simple tones (i.e., neither meaningfully related stimuli nor incongruent). In addition, as was the case in the Busse et al. study, no effects of multisensory attentional context (i.e., whether the synchronous visual stimulus was attended or not) were found on the auditory response earlier than the frontal negativity starting after 200 ms. This is in contrast with studies in which the auditory stimulus occurs in the spatial locus of attention (either visually directed or auditorily directed spatial attention), which typically results in an enhanced auditory N1 sensory component at 100 ms, relative to when spatial attention is directed elsewhere (Talsma et al., 2005; Woldorff et al., 1991). Thus, this multisensory late-negativity effect can be interpreted as attention having to spread first from the visual to the spatially separated but synchronous auditory stimulus component, which apparently takes about 200 ms or so, before any attention related effects can be expressed in the auditory extracted ERPs (Busse et al., 2005). Our current data, collapsed across congruency, thus replicated these earlier results.

Multisensory Spread of Attention as a Function of Visual-Auditory Incongruency

Analysis of the spreading-of-attention activity separately for congruent and incongruent stimulus combinations indicated that it started at the same time (~220ms) in both cases, thus being independent of the stimulus identity (incongruent/congruent). Later in time, however, the attentional-spreading activity was larger for the incongruent stimulus combination than for the congruent, a difference that began at around 300 ms and was significant during two later windows (300-380 and 540-560 ms).

In regards to the observed *amplitude* differences in the spreading-of-attention activity between incongruent and congruent combinations, we had hypothesized two alternative possible outcomes. One possibility was that attention would spread more to the task-irrelevant auditory stimulation for the congruent than for the incongruent trials; because once the incongruency was detected the brain would respond by sending inhibitory signals to suppress the processing of the conflicting auditory stimulus. The alternative hypothesis was that the incongruent auditory stimulation would serve as a greater distractor, tending to capture attentional resources and thus lead to a higher amplitude in the extracted auditory ERP's. Our results showing increased spreading of attention for the incongruent stimulus trials clearly provide evidence for the second hypothesis. In addition, these incongruency differences were only found when the visual component was attended, and not when it was unattended. Thus, our results would be consistent with various previous unimodal visual ERP studies using higher level, top-down, stimuli (Flanker paradigm; Wendt et al., 2007; Bartholow et al., 2005; Heil et al., 2000), Stroop paradigm; Liotti et al., 2000; Appelbaum et al., 2009; West and Alain, 1999; Badzakova-Trajkov et al., 2008) that have shown increased processing for the incongruent (conflicting) versus congruent stimulus combinations. We interpret the present results as reflecting an increased tendency of the task-irrelevant incongruent auditory stimulus to attract a greater level of attention.

In regards to the *temporal onset* of the spreading/conflict interaction, we suggested two possible outcomes. One was that there could be a relatively immediate influence of conflict on spreading, in that conflict effects and attentional spreading effects show similar onsets, at least as reported across studies (e.g. Wendt et al., 2007 (conflict) versus Busse et al., 2005 (spread)). Another possibility was that the influence of conflict on attentional spreading might be somewhat delayed, under the view that the simultaneous auditory stimuli might have to be drawn at least partially into the penumbra of the visual attention, and/or to reach a higher enough processing level after receiving some attention, before its conflicting nature would be detected and differentially responded to. Our results provide evidence for the delay hypothesis (conflict interaction effect being delayed, here until 300 ms), presumably reflecting that conflict was detected after some spreading of attention to the task-irrelevant incongruent auditory stimulus had occurred.

Relationship to Supramodally Focused Spatial Attention Paradigms

In most previous EEG and MEG studies investigating conflicting versus matching auditory-visual stimuli (e.g. face/voice: Stekelenburg and Vroomen, 2007, picture/sound: Fiebelkorn et al., 2010; Yuval-Greenberg and Deouell, 2007; letter/sound: Raji et al., 2000; Herdman et al., 2006), the stimuli were generally presented from the same spatial location, typically centrally (but see with fMRI: Fairhall and Macaluso, 2009). In such studies, spatial attention was thus already in place for the location of both the visual and auditory stimuli (i.e., supramodally) and did not need to spread *spatially* to encompass the simultaneously occurring auditory stimulus. When the auditory stimuli are presented at the same location as the attended visual stimulus, however, it cannot be distinguished if any observed multisensory conflict effects depend on attention, at least on spatial attention, or could occur

also without being in the spatial attentional focus (i.e., there is no unattended spatial condition to compare to).

Note, that in the present study, the task-irrelevant auditory stimulus was always the same, always occurring centrally, with the multisensory attentional manipulation being whether the simultaneous lateral visual stimulus was in a spatially attended location versus a spatially unattended one, with the contrast between these enabling an isolation of the attentional spreading effect. Moreover, our data indicate that there is multisensory conflict interaction only when the simultaneous task-relevant visual component is presented in the spatially attended location, with no effect of incongruency when it occurs in a spatially unattended location.

Stimulus-related versus Representation-related Multisensory Attention Effects

In a recent study by Fiebelkorn and colleagues (2010) investigating multisensory conflict processing of over-learned image/sound combinations it was proposed that the multisensory spreading attention could be either mainly stimulus driven or mainly representation driven. In that study, all the stimuli were presented centrally at a spatially attended location, but with only the images being task-relevant. The images were of three different objects types (dogs, cars, and guitars), and in separate runs one type of these was designated as the target object type, with the task to focus their object attention on those and perform a one-back working memory task. On some trials, a task-irrelevant sound was presented that could be either congruent with the image (a barking sound with a dog) or incongruent (a car sound with a dog), and on some trials the image was presented alone. Using a series of ERP subtractions, the authors aimed to separate stimulus-driven attentional spreading from representation-driven attentional spreading, the first being a bottom-up process dependent on physical stimulus properties and the synchronous occurrence of the visual and auditory components, and the latter dependent on the task-relevance of the stimuli (target/nontarget). For the stimulus-driven spreading in that study, an onset timing of ~240 ms over fronto-central electrodes sites was found, but the amplitude of this activity in the 200-300 ms time range was independent of the identity (incongruent/congruent) of the auditory and visual components. Thus, in this time range, our results agree with the Fiebelkorn et al. ones, showing no effect of incongruency on this initial, bottom-up attentional spreading activity, derived from the simultaneous occurrence of the visual and auditory components.

On the other hand, we observed greater attentional spreading activity later on, beginning at around 300 ms, for the incongruent stimulus combinations. While the Fiebelkorn et al study focused on the initial time period for this effect, prior to 300 ms, showing no influence of incongruency there, the attentional spreading effect in their data lasts for an extended period of time, as it did in our study. Of potential relevance is that if one looks carefully at their data traces, it would appear that, later on, as in our data, there was substantially greater attentional spreading activity for the incongruent condition (compare traces for congruent “audiovisual (AV-V)” non-targets in their Figure 4a and incongruent “audiovisual (AV-V)” non-targets in their Figure 4b; Fiebelkorn et al., 2010, page 114), with this enhanced activity for the incongruent condition running from about 300 till the end of Figure traces at 500 ms. The authors do not report statistical results from this later latency range, and it may well have only been a trend, but such a difference would appear to be quite consistent with our results. In terms of their suggested model of distinguishing between stimulus-driven and representation-driven attentional spreading, we would interpret these results in the following way: This attentional spreading effect begins in a bottom-up, stimulus-driven way, with initially no difference as a function of congruency. However, after the attentional spread has proceeded for some period of time, the auditory and visual component processing reaches a representational level of analysis, at which time their conflicting nature is detected, triggering this later conflict-related difference. Thus, in this view, the stimulus-driven

attentional spread is indeed initially fully bottom-up, unrelated to representation and just resulting from the visual and auditory component co-occurrence, but an interaction can occur when the processing reaches a representational level. We note that this influence of representation would appear to be different from the representation-related effect that Fiebelkorn and colleagues (2010) were focusing on, in which the representation-driven attentional spreading is due to the top-down, representation-based attention to a specific category of object type (e.g., dogs versus cars), with this task-related top-down manipulation inducing its own multisensory attentional spreading activity. Since in our study we focused on a manipulation of visual spatial attention, rather than on a manipulation of attending to one type of object versus another (i.e., in our case, this might have been comparing attending to “A’s” versus attending to “X’s”), our data cannot comment on this other aspect of representation-driven, fully top-down task-related effects examined by Fiebelkorn and colleagues (2010).

Semantically-related N400 effects and the Influence of Spatial Attention

In the present study the comparison of the response to an incongruent versus a congruent central auditory stimulus that was paired with a visual stimulus in a spatially attended location gave a robust incongruency effect, but no such effect of incongruency was seen when the visual stimulus was in the *unattended* location (see design Fig.1 & traces Fig.7). An ERP-activation to which our results may be related is the N400 wave, which is a late negative-polarity component sensitive to semantic incongruity that peaks at around 400 ms post-stimulus. (Kutas and Hillyard, 1980). Importantly, the N400 is also an indicator of semantic incongruity of two sequential presented words or pictures, i.e. mismatching pairs (e.g. unrelated words) reveal an increased N400 compared to matching pairs (e.g. related words) (reviewed in Van Petten & Luka, 2006). A previous study by McCarthy and Nobre (1993) investigated the interplay of spatial attention and semantic processing by presenting two visual streams of words to different spatial location on the screen, one of which was spatially attended and one unattended. The typical N400 negativity peaking at 400ms, revealed by semantically unrelated versus related words, could only be found in the spatially attended visual stream, and not in the spatially unattended one. Analogously, in the present study we found that multisensory ‘semantic-object’ processing also depended on attention, in our case due to the multisensory attentional context (i.e., it only occurred when the simultaneous, spatially discordant, visual stimulus component was attended). On the other hand, the typical N400 distribution tends to be more posteriorly distributed (i.e. central-parietal, Van Petten & Luka, 2006) than the more anterior (frontal-central) distribution we find for the negative-polarity enhancement here. Nevertheless, it is possible that the current attention-dependent, multisensory, letter-incongruency effect reported here may bear some relationship to other previously reported, attention-dependent, negative-polarity activations that are sensitive to semantic incongruency more generally.

Summary and conclusion

In summary, we investigated ‘spreading-of-attention’ across a multisensory audiovisual object when the auditory and visual stimulus components were spatially discordant and semantically conflicting. Attentional spreading started at around 220 ms over frontal-central sites, for both congruent and incongruent trials types, as reflected by a slow frontal-central negativity, replicating the results that were reported in Busse et al. (2005) for simple visual and auditory stimuli that were neither meaningfully related or unrelated. In addition, this frontal-central negativity was specifically larger at later time points (300-360 ms and 540-560 ms) for incongruent than for congruent stimulus components. We conclude that the increased frontal-central negativity for the incongruent condition, which occurred some time after the onset of attentional spreading, indicates an increased attentional capture for this condition that occurs after attention has spread from the task-relevant visual to the task-

irrelevant but conflicting auditory stimulus part, presumably as a result of some degree of multisensory higher-level processing interactions. Future studies, using methods with higher spatial resolution (e.g., fMRI), will be required to investigate whether this effect reflects increased activity only in auditory sensory cortex (cf. Busse et al., 2005) for the incongruent auditory stimulus, or whether it also includes additional activity from other brain areas in frontal cortex, such as the anterior cingulate cortex, that have been implicated as being involved in conflict detection and resolution.

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Figure 1.

Task paradigm, shown for runs with subjects' attention to the left side. Two visual letter-streams were presented randomly to the left and right visual fields, including two task-relevant letters ('A', 'X'). The task of the subject was to fixate on the central white cross, attend to the stream on a designated side, and press a button for a switch of visual letters in a sequential pair (2-AFC) on that side. To reduce button-press-related activity, targets requiring a button press comprised only 15% of the trials, allowing for analysis of attended versus unattended nontarget responses, free of target-related and motor-related processing. Two-thirds of the lateral visual letters (both attended and unattended) were accompanied by simultaneous, centrally presented, spoken letter sound, 50% of which were incongruent, 50% congruent with the visual letter. Importantly, subjects were instructed to ignore the central spoken letters.

Figure 2.

Evidence for subject's covert visual attention: modulation of visual sensory activity due to the selectively focused visual spatial attention. (A) Left visual ROI: Traces of the attentional modulation of the visual N1 component contralateral to the right side of pure visual stimulation. The traces were revealed by averaging over four electrodes over left parietal-occipital scalp (*light green markers in center panel*), separately for when the visual stimuli were attended versus unattended. (B) Right visual ROI: Traces of the attentional modulation of the visual N1 component contralateral to the left side of pure visual stimulation. The traces were revealed by averaging over four electrodes over right parietal-occipital scalp (*dark green markers in center panel*), separately for when the visual stimuli were attended versus unattended. Note that the enhancement of the N1 sensory response when the visual stimuli were attended.

Figure 3.

Schematic illustration of the extraction of auditory ERPs to reveal attentional spreading shown at frontal site Z4 (~Fz). (Left) Attended condition: A mixture of auditory and visual components can be seen in the ERP to the combined audiovisual letter/sound combinations independent of whether they were coupled to a congruent or incongruent sound; *brown trace*). The subtraction of the visual-alone ERP (*green trace*) from the audiovisual ERP yields the “extracted” ERPs to the sound (con/inc) in the context of an attended visual letter (*grey solid line*). (Right) Unattended condition: The analogous subtraction is performed on the unattended unisensory visual letters (*green dotted trace*) and the unattended audiovisual letter/sound combinations (*brown dotted line*). The *grey dotted trace* shows the corresponding unattended-condition difference wave of the multisensory minus unisensory-visual ERPs. (Bottom) The extracted difference waves overlaid, revealing the attention-related difference of a task-irrelevant, spatially discordant, spoken letter sound occurring in the context of an attended versus unattended visual letter stimulus (i.e. attentional spread activity *orange markers*).

Figure 4.

Spread of attention averaged over congruent and incongruent trials. (A) Traces of extracted auditory ERP averaged over the frontal-central ROI (B) for a centrally presented ignored sound with an attended (*line*) or unattended (*dotted*) visual letter from a lateral position. Note, that the attended-visual and unattended-visual traces start to diverge at around 220 ms, indicating the start of attentional spread. (B) Top view topographical display of the locations of four electrode sites included in the frontal-central ROI (*red dots*); locations are averaged over 16 subjects. (C) Scalp topographies of the differences of the attended minus unattended traces of (A), showing the spread of visual attention, collapsed over congruency conditions.

Figure 5.

Traces of the spread of visual attention, shown separately as a function of multisensory incongruency for the frontal-central ROI. Left panel (A): Traces of the extracted auditory ERPs for sounds congruent with an attended (*solid line*) or unattended (*dotted line*) visual letter, for the fronto-central ROI. Central panel (B): Corresponding traces of the extracted auditory ERP for sounds incongruent with an attended (*solid line*) or unattended (*dotted line*) visual letter. Right panel (C): Traces of extracted auditory ERP for the attentional differences of (A) and (B), thus showing the interaction of attention and congruency. Black arrows mark the interval of significant interaction.

Figure 6.

Scalp topographies of the spread of visual attention, shown separately as a function of multisensory incongruency. Upper panel (A): Scalp topographies of congruent attentional spread revealed by the difference of incongruent sounds with an attended minus unattended visual letter, shown in successive 50-ms bins (cf. Fig 4A). Central panel (B): Corresponding scalp topographies of incongruent attentional spread revealed by the difference of incongruent sounds with an attended minus unattended visual letter (cf. Fig 4B). Bottom panel (C): Scalp topographies of the interaction of attentional spread by congruency; thus indicating the difference in incongruent (B) minus congruent (A) scalp topographies.

Figure 7.

Traces and corresponding scalp topographies of conflict processing, shown separately as a function of visual attention. Left panel (A): Traces of the extracted auditory ERPs for the centrally presented sounds when they either congruent (*pink line*) or incongruent (*blue line*) with a simultaneous, **attended**, visual letter, shown for the fronto-central ROI. Lower panel (B): Scalp topographies of the incongruency effects shown in (A) when the simultaneous visual stimulus was attended, shown in successive 50-ms bins (cf. Fig 7A). Right panel (C): Traces of the extracted auditory ERPs for sounds congruent (*pink dots*) or incongruent (*blue dots*) with a simultaneous, **unattended** visual letter, shown for the same fronto-central ROI. Note that there was no effect of incongruency when the simultaneous, laterally presented, visual stimulus was unattended.