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Electrophysiological correlates of change detection

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Abstract

To identify electrophysiological correlates of change detection, event-related brain potentials (ERPs) were recorded while participants monitored displays containing four faces in order to detect a face identity change across successive displays. Successful change detection was mirrored by an N2pc component at posterior electrodes contralateral to the side of a change, suggesting close links between conscious change detection and attention. ERPs on undetected-change trials differed from detected-change and no-change trials. We suggest that short-latency ERP differences between these trial types reflect trial-by-trial fluctuations in advance task preparation, whereas differences in the P3 time range are due to variations in the duration of perceptual and decision-related processing. Overall, these findings demonstrate that ERPs are a useful tool for dissociating processes underlying change blindness and change detection.

Descriptors: Consciousness, Change blindness, Change detection, Selective attention, Event-related brain potentials

The study of the neural correlates of consciousness has become one of the most active research areas in cognitive neuroscience (for recent reviews, see Kanwisher, 2001; Rees, Reimann, & Koch, 2002). Functional brain imaging studies have used different experimental paradigms, such as visual masking (Bar et al., 2001), binocular rivalry (Tong, Nakayama, & Kanwisher, 1998), or change blindness (Beck, Rees, Frith, & Lavie, 2001; Pessoa & Ungerleider, 2004), to identify brain areas involved in conscious awareness. These studies have shown that changes in the content of visual awareness are correlated with selective activations of ventral visual areas, even when physical stimulation parameters remain unchanged, thereby suggesting that the ventral visual stream may be necessary for generating conscious visual experience.

The phenomenon of change blindness can provide important insights into the mechanisms and neural substrates of conscious awareness. Change blindness refers to the fact that salient changes in visually presented scenes often remain undetected when displays are separated by a blank interval (see O'Regan, Rensink, & Clark, 1999; Rensink, O'Regan, & Clark, 1997; Simons, 2000; Simons & Levin, 1997). Observers' inability to detect prominent changes across displays demonstrates surprising limitations in the conscious representation of visual scenes and suggests that focal attention is critically involved in conscious change detection. In line with this hypothesis, results from recent fMRI studies (Beck et al., 2001; Huettel, Güzeldere, & McCarthy, 2001) have shown that change detection is not only linked to an activation of extrastriate ventral visual areas, but also involves activity in dorsal frontoparietal regions that are commonly implicated in the control of selective attention.

Recently, event-related brain potential (ERP) measures have been employed as a means to gain insights into the time course of neural events underlying change blindness and change detection. Niedeggen, Wichmann, and Stoerig (2001) presented observers with an alternating set of scenes containing alphanumeric stimuli, and found that the detection of a change gave rise to an enhanced positivity in the P3 time range (see also Turatto, Angrilli, Mazza, Umiltá, & Driver, 2002, for similar findings). Koivisto and Revonsuo (2003) have studied electrophysiological correlates of conscious change detection in an experiment where two displays containing eight rectangles were presented successively, and observers had to report at the end of each trial whether or not one of these rectangles had changed orientation across displays. Change detection was linked to a negative amplitude modulation at posterior electrodes, which started about 200 ms after stimulus onset. In addition, a later broadly distributed enhanced positivity was found for detected-change as compared to undetected-change trials, similar to the results earlier reported by Niedeggen et al. and Turatto et al. Koivisto and Revonsuo suggested that the posterior negativity is an electrophysiological correlate of phenomenal visual change awareness, whereas the subsequent enhanced positivity may be linked to later postperceptual processing stages involved in response-related decision processes.

The present ERP study was conducted to shed further light on the processes involved in change detection by identifying electrophysiological markers of change processing. Similar to Koivisto and Revonsuo (2003), we recorded ERPs in a situation where participants monitored two successively presented stimulus displays in order to detect a change across displays. To make the task situation more compatible with behavioral demonstrations of change blindness, which have typically used real-world visual scenes, the changes in our experiment did not

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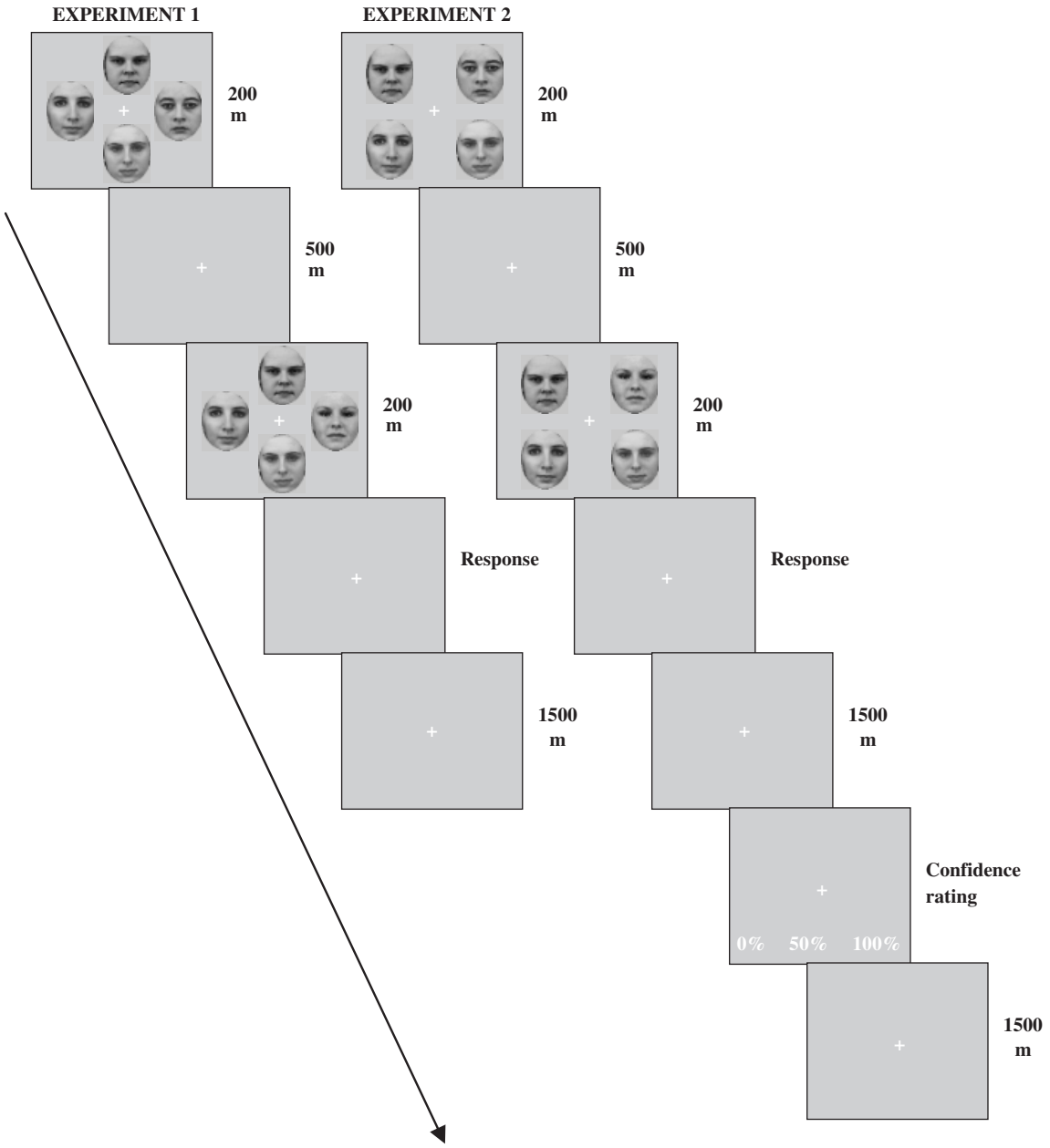

Figure 1. Stimulus setup used in Experiment 1 (left side) and in Experiment 2 (right side). Display sequences illustrate trials where a face identity change occurred to the right of fixation.

involve simple features such as orientation, but were more complex. Displays consisted of four faces with neutral facial expression. On two thirds of all trials, one of these faces changed identity across displays (see Figure 1). Participants were instructed to maintain central fixation and to report at the end of each trial whether or not they had detected a change. In Experiment 1, faces were located above, below, and to the left and right of fixation (Figure 1, left side). Here, only faces presented to the left or right of fixation (but never the faces presented at the top or bottom) could change identity across displays, and participants were informed of this fact.[1] In Experiment 2, faces were presented in each of the four quadrants of the visual field, and changes could occur with equal probability at any of these four locations. Here, participants were also required to rate their subjective confidence with respect to the accuracy of their perceptual judgment at the end of each trial (Figure 1, right side).

To uncover electrophysiological correlates of conscious change detection, we compared ERPs triggered in response to the second display on trials where this display contained a face change as a function of whether participants reported being aware of this change (detected-change trials) or reported not to have seen a change (undetected-change trials). These two types of trials are equivalent with respect to the physical presence of a change, but differ with respect to participants' reported change awareness. Thus, systematic ERP differences between these trials might reflect neural processes responsible for change detection.

[1]Faces at the top and bottom positions were included in Experiment 1 to increase overall task difficulty. Pilot studies had shown that face changes on the left or right side were detected less frequently when additional task-irrelevant faces were added to the stimulus display.

When looking for electrophysiological markers of change detection, we were particularly interested to investigate the possibility that such ERP markers might be sensitive to the location where a change occurs (left vs. right of fixation). We tested the hypothesis that change awareness might be closely linked to the N2pc component, which has previously been observed in experiments investigating the allocation of attention in visual search tasks (cf. Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999, 2003a, 2003b). The N2pc is typically elicited at poststimulus latencies of 200 to 300 ms at posterior electrodes contralateral to the side of a task-relevant visual event, such as a target in a visual search task, and is assumed to reflect the spatially selective attentional processing of such events. If change detection was closely related to focal attention, as is generally assumed (cf. Rensink et al., 1997), it is plausible to assume that observers' successful detection of a change is accompanied by an ERP component that reflects the allocation of attention. In previous studies of change detection and change blindness (Koivisto & Revonsuo, 2003; Niedeggen et al., 2001; Turatto et al., 2002), ERPs were not analyzed as a function of the side where a change occurred. To investigate the hypothesis that change awareness is reflected by the N2pc component, we compared ERPs elicited on detected-change and undetected-change trials separately for trials where changes occurred to the left or to the right of fixation.

A second set of analyses compared ERPs elicited on undetected-change trials (where participants failed to report the presence of a change) to ERPs on trials where no change occurred and participants correctly reported the absence of any change (no-change trials). These two types of trials differ with respect to the presence versus absence of a physical change, but are equivalent with respect to participants' reported perceptual awareness (i.e., no change detected). Thus, any ERP differences between these trial types might be interpreted as evidence for the implicit processing of a change (see Fernandez-Duque, Grossi, Thornton, & Neville, 2003; Thornton & Fernandez-Duque, 2002).

EXPERIMENT 1

Methods

Participants

Eighteen healthy paid volunteers participated in the experiment, after giving their written informed consent. Two participants were excluded from analysis because their average detection rate for changes on one side (changes in the left visual field for one participant and changes on the right side for the other participant) was less than 8%, whereas they detected more than 89% of all changes on the opposite side. Thus 16 participants (7 women, 9 men, aged 22–37 years, mean age 28 years) remained in the sample. Fifteen participants were right-handed, 1 was left-handed, and all reported normal or corrected-to-normal vision. The experiment was performed in accordance with the relevant institutional guidelines, and was approved by the Ethics Committee, School of Psychology, Birkbeck College.

Stimuli and Apparatus

Participants sat in a dimly lit sound-attenuated cabin at a viewing distance of 60 cm from a 15-in. computer monitor, with response keys under their left and right index fingers. Stimuli were black-and-white photographs of the faces of 32 different individuals (16 females and 16 males with neutral facial expression). These stimuli were digitally processed by graphics software so that each face had the same oval shape ($2.9^\circ \times 3.8^\circ$ visual angle). On each trial, two stimulus displays were presented successively against a gray background (see Figure 1). Displays consisted of four faces located at the 3, 6, 9, and 12 o'clock positions at a constant distance of 4.3° from a central fixation cross, which subtended $0.5^\circ \times 0.5^\circ$ visual angle and was continuously present throughout each block.

Procedure

The experiment consisted of 12 blocks, with 72 trials per block. On each trial, two displays containing four different faces were presented successively for 200 ms each, and were separated by an empty interval of 500 ms. Intertrial interval was 1500 ms. On 24 trials per block, both displays were identical (no-change trials). On the remaining randomly intermingled 48 trials, the face located on the left or the right of fixation was replaced by a different face in the second display, whereas the other three faces remained identical across displays (change trials). Changes on the left and right sides occurred in random order and with equal probability, and always consisted of a male face being replaced by another male face, or a female face by another female face (i.e., there was never any gender change across displays). Faces located at the top and bottom positions never changed across displays, and participants were informed about this fact prior to the start of the experiment.

Participants were given printed and verbal instructions to maintain their gaze focused on the central fixation cross, and to report whether or not they had noticed a change across the two displays by pressing the left or right response key at the end of each trial. Speed and accuracy were emphasized equally. In six successive blocks, participants pressed the left key to indicate change detection and the right key to indicate the absence of a change, and these response assignments were reversed in the other six blocks. Prior to the start of the first six experimental blocks, participants performed one training block consisting of 12 no-change and 24 change trials, in order to familiarize them with the task. Another training block was performed prior to the start of the other six blocks, where response assignments were reversed.

EEG Recording and Data Analyses

EEG was recorded with Ag-AgCl electrodes and linked-earlobe reference from FPz, F7, F3, Fz, F4, F8, FC5, FC6, T7, C3, Cz, C4, T8, CP5, CP6, P7, P3, Pz, P4, P8, and Oz (according to the 10–20 system), and from OL and OR (located halfway between O1 and P7 and O2 and P8, respectively). Horizontal EOG (HEOG) was recorded bipolarly from electrodes positioned on the outer canthii of both eyes. Impedance was kept below 5 KΩ for all electrodes, amplifier bandpass was 0.1 to 40 Hz, and digitization rate was 200 Hz. EEG and HEOG were epoched off-line into 1600-ms periods, starting 100 ms prior to the onset of the first display. Trials where horizontal eye movements (HEOG exceeding $\pm$ 30 μV) were detected in the interval between the onset of the first display and 600 ms after the onset of the second display were discarded from analysis. Trials with eyeblinks or other artifacts (any electrode exceeding $\pm$ 80 μV) in the 600-ms interval following the onset of the second display were also excluded. After artifact rejection, averages were computed on the basis of the EEG elicited in response to the second display, rel-

ative to a 100-ms interval preceding display onset. Separate averages were computed for change trials and no-change trials. For change trials, averages were computed as a function of change location (left vs. right changes) and change detection (detected-change trials vs. undetected-change trials). For no-change trials, only trials with correct responses (i.e., correct rejections) were averaged. At least 30 epochs per condition were available after artifact rejection for all participants to compute averages for detected-change, undetected-change, and no-change trials, respectively.

Two separate sets of analyses were conducted. In the first set of analyses, ERPs elicited on change trials in response to the second display containing a changed face on the left or right side were analyzed as a function of whether participants reported having been aware of this change or not. Repeated-measures ANOVAs were conducted separately for lateral anterior sites (F3, FC5, F4, FC6), lateral central sites (C3, CP5, C4, CP6), and lateral posterior sites (OL, P3, OR, P4), as well as for midline electrodes (Fz, Cz, Pz), for the factors change detection (detected-change vs. undetected-change trials), change location (left vs. right), electrode site (F3/4 vs. FC5/6; C3/4 vs. CP5/6; OL/R vs. P3/4; Fz vs. Cz vs. Pz), and recording hemisphere (left vs. right, for lateral electrode pairs only). In the second set of analyses, ERPs on undetected change trials and no-change trials were analyzed together. Factors were the same as in the first set of analyses, except that the factor change detection was replaced by the factor presence of change (undetected-change vs. no-change trials), and the factor change location was omitted (because this factor could not be applied to no-change trials). All analyses were conducted on mean amplitude values obtained for measurement windows centred on the poststimulus latencies of the P1 (90–130 ms), N1 (160–200 ms), N2 (240–340 ms), and P3 (500–700 ms) components.

Results

Behavioral Performance

Participants correctly reported the absence of a change on 91% of all no-change trials and detected a change in the second display on 71% of all change trials (change blindness: 29%). Observers were more accurate on no-change trials as compared to trials containing left changes (70%) or right changes (72%), both $t(15) > 4.6$, both $p < .001$. Change detection performance (error rates and response latencies) did not differ as a function of change location (left vs. right). Reaction times (RTs, $\pm$ *SD*) were delayed on undetected-change trials (707 $\pm$ 127 ms), relative to no-change trials (625 $\pm$ 103 ms, $t(15) = 6.6$, $p < .001$) and to detected-change trials (658 $\pm$ 120 ms, $t(15) = 2.94$, $p < .01$). In contrast, RTs on detected-change trials and no-change trials did not differ significantly.

ERP Results: Detected-Change Trials versus Undetected-Change Trials

Figure 2 shows ERPs elicited on change trials in response to the second display, separately for trials where the change was reported (solid lines) and for trials where participants reported being unaware of a change (dashed lines). Waveforms are shown separately for electrodes contralateral and ipsilateral to the side of a change (left and right panels), as well as for midline electrodes (bottom panel). ERPs differed substantially as a function of change detection. First, at very short latencies (i.e., starting within less than 40 ms after stimulus onset), ERPs on trials where changes were successfully detected were more negative than on trials where participants missed the presence of a change. This detection-related negativity was broadly distributed across anterior, central, and posterior sites, and overlapped with the P1 and N1 components. Next, an enhanced negativity was triggered on detected-change trials in the N2 time range at posterior electrodes contralateral to the side where this change occurred (N2pc in Figure 2). Finally, starting at about 350 ms poststimulus, a broadly distributed sustained positivity for detected-change as compared to undetected-change trials was observed.

These informal observations were in turn substantiated by statistical analyses. In the P1 analysis window (90–130 ms poststimulus), main effects of change detection were present at lateral posterior, central, and anterior electrodes, as well as at midline sites, all $F(1,15) > 15.9$, all $p < .001$, reflecting the broadly distributed early negativity for detected-change trials visible in Figure 2. A similar pattern of results was found for the N1 analysis interval (160–200 ms poststimulus). Again, the enhanced negativity for detected-change trials was mirrored by main effects of change detection at all analyzed sites, all $F(1,15) > 5.5$, all $p < .04$.[2]

To demonstrate that these effects do not represent genuine amplitude modulations of early visual P1 and N1 components, but instead reflect an early sustained negativity on detected-change trials, which is superimposed on both components, an additional analysis was conducted for ERP mean amplitudes elicited between 30 ms and 80 ms poststimulus, that is, prior to the onset of the P1 component. Again, main effects of change detection were found for all recording sites, all $F(1,15) > 8.6$, all $p < .01$, due to the early onset of the enhanced negativity on detected-change relative to undetected-change trials (see Figure 2). Change Detection $\times$ Recording Hemisphere and Change Detection $\times$ Change Location $\times$ Recording Hemisphere interactions were entirely absent in all analyses of ERPs elicited within the first 200 ms after stimulus onset, demonstrating that the early detection-related negativity was not lateralized.

In the subsequent N2 analysis window (240–340 ms poststimulus), no significant main effects of change detection were obtained at midline sites or at lateral anterior and central electrodes. In contrast, a main effect of change detection was present at lateral posterior electrodes, $F(1,15) = 8.7$, $p < .02$, and was accompanied by a significant three-way interaction between change detection, change location, and recording hemisphere, $F(1,15) = 15.0$, $p < .001$. As can be seen in Figure 2, an enhanced N2 was elicited on detected-change trials at posterior electrodes contralateral to the side of a change (N2pc), but not at ipsilateral electrodes.

To further ascertain the status of this N2pc component as an electrophysiological indicator of change detection, additional analyses were conducted separately for detected-change trials and for undetected-change trials. On trials where participants reported to be aware of a change, a highly significant Change Location $\times$ Recording Hemisphere interaction at lateral posterior electrodes, $F(1,15) = 21.7$, $p < .001$, reflected the presence of the N2pc. In contrast, this interaction was entirely absent on

[2]At lateral posterior sites, a significant Change Awareness $\times$ Electrode Site was present in the N1 analysis window, $F(1,15) = 10.2$, $p < .01$. Subsequent analyses revealed that a significant effect of change awareness on N1 amplitudes at P3/4, but not at OL/R.

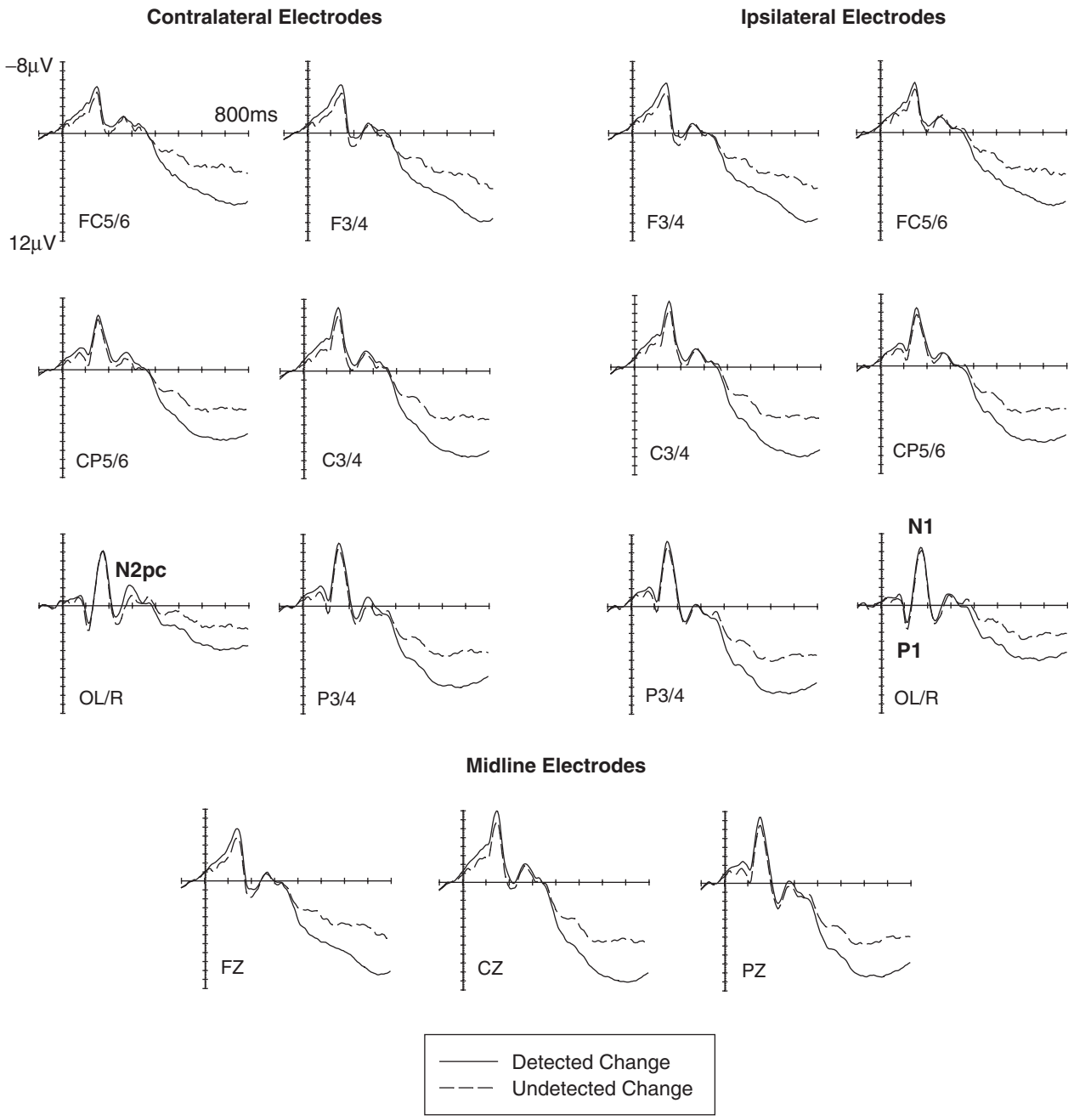

Figure 2. Grand-averaged ERP waveforms triggered in Experiment 1 on change trials in response to the second stimulus display at electrodes contralateral and ipsilateral to the side where the change occurred (left and right panels) and at midline electrodes (bottom panel). ERPs are shown separately for trials where participants reported being aware of a change (detected-change trials, solid lines), and for trials where they reported not seeing any change (undetected-change trials, dashed lines).

undetected-change trials, $F < 1$.[3] This pattern of results is illustrated in Figure 3 (top), which shows ERPs at occipital electrodes OL/R contralateral (solid lines) and ipsilateral (dashed lines) to the side of a change for detected-change trials (left side) and undetected-change trials (right side). An enhanced contralateral negativity (N2pc) was elicited on detected-change trials, but was completely absent on trials where participants failed to report the presence of a change.

Figure 3 (bottom) shows the N2pc on fast detection trials (where response times were within the fastest 30% of individual response time distributions, left side) and on slow detection trials (where response times fell within the bottom 30%, right side). To formally assess the relationship between the timing of change detection and N2pc onset latency, a further analysis was performed on difference amplitudes obtained on detected-change

[3]In an analogous analysis conducted for lateral central electrodes, an Electrode Site × Change Location × Recording Hemisphere interaction, $F(1,15) = 8.6$, $p < .01$, was found for detected-change trials, and subsequent analyses revealed a significant Change Location × Recording Hemisphere interaction for CP5/6, $F(1,15) = 10.5$, $p < .01$, but not for C3/4.

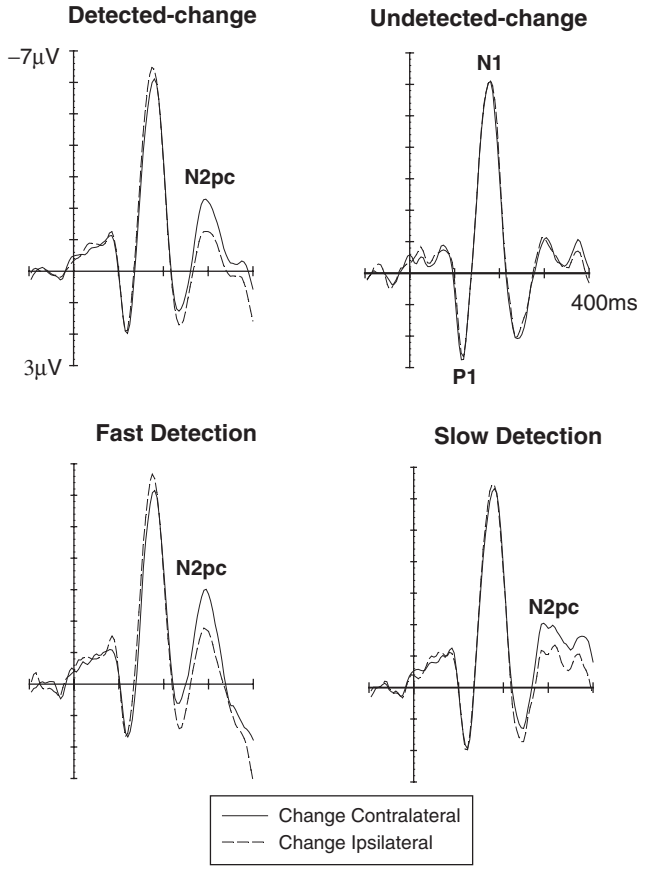

Figure 3. Grand-averaged ERPs elicited in Experiment 1 on change trials in response to the second display at occipital electrodes OL/OR contralateral (solid lines) and ipsilateral (dashed lines) to the side where the change occurred. Top panels: ERPs for trials where observers successfully detected the change (detected-change trials, left side) or reported being unaware of a change (undetected-change trials, right side). Bottom panels: ERPs on detected change trials with responses within the fastest 30% of individual response time distributions (fast detection trials, left side) and on detected change trials with the 30% slowest detection responses (slow detection trials, right side).

trials by subtracting ERPs triggered at occipital electrodes ipsilateral to the side of the change from contralateral occipital ERPs, separately for fast and for slow detection trials. N2pc onset was determined by testing via t tests whether the resulting difference amplitudes differed significantly from zero for each successive sampling point in the 200–300-ms poststimulus interval. To avoid α error resulting from multiple comparisons, a significant p value was accepted as an accurate indicator of N2pc onset only if this difference remained significant for at least four successive sampling points. For fast detection trials, a significantly enhanced contralateral negativity emerged 215 ms after stimulus onset, $t(15) = 2.2$, $p < .05$, and remained significant for all successively tested sampling points, all $t(15) > 2.9$, all $p < .01$. In contrast, the contralateral–ipsilateral difference wave for slow detection trials differed reliably from zero only from 270 ms poststimulus onwards, all $t(15) > 2.6$, all $p < .02$. This result confirms that the N2pc tended to be elicited earlier on trials where detection responses were fast (see Figure 3, bottom).

Finally, in the P3 latency range (500–700 ms poststimulus), main effects of change detection were present at all recording sites, all $F(1,15) > 22.6$, all $p < .001$, reflecting a broadly distributed enhanced positivity on detected-change relative to undetected-change trials (see Figure 2).

ERP Results: Undetected-Change Trials versus No-Change Trials

Figure 4 shows ERPs elicited on change trials where participants were unaware of the presence of a change (undetected-change trials, solid lines) and on no-change trials (dashed lines). A broadly distributed enhanced negativity was present for no-change relative to undetected-change trials at short latencies, which appeared to overlap with the P1 and N1 components. This was reflected in the P1 time window by main effects of the factor presence of change at lateral anterior, central, and posterior electrodes, as well as at midline sites, all $F(1,15) > 5.7$, all $p < .03$. In the N1 time range, the same effect only approached significance at midline sites, $F(1,15) = 3.7$, $p < .08$, and at lateral central electrodes, $F(1,15) = 3.3$, $p < .09$. As before, an additional set of analyses was conducted to investigate whether these effects represent a sustained negativity superimposed upon P1 and N1 components, which starts prior to P1 onset. For ERP mean amplitudes elicited between 30 ms and 80 ms poststimulus, a main effect of presence of change was found for lateral central sites, $F(1,15) = 4.6$, $p < .05$, and this effect was almost significant at lateral anterior electrodes, $F(1,15) = 4.4$, $p < .06$, demonstrating the presence of a very early sustained negativity for no-change relative to undetected-change trials (see Figure 4).

No effects of presence of change were obtained in the N2 latency window (240–340 ms poststimulus). At longer latencies, no-change trials were more positive than undetected-change trials, and this was reflected in the P3 time range (500–700 ms poststimulus) as main effects of presence of change at all recording sites, all $F(1,15) = 14.5$, all $p < .002$. No Presence of Change $\times$ Recording Hemisphere interactions were obtained in any analysis comparing undetected-change and no-change trials, demonstrating that the ERP differences between these two types of trials were not lateralized.

Discussion of Experiment 1

In Experiment 1, three successively elicited ERP modulations were found to be sensitive to change detection. An enhanced negativity was elicited at very short latencies on detected-change and no-change trials relative to undetected-change trials. In the N2 time range, an enhanced negativity was triggered at posterior electrodes contralateral to the side of a change for detected-change trials, but not for undetected-change trials. Finally, a broadly distributed enhanced positivity was observed for detected-change and no-change trials as compared to undetected-change trials in the P3 latency range.

Turning first to the amplitude modulations observed at very short latencies (sustained negativities for detected-change trials and no-change trials relative to undetected-change trials), it is notable that these modulations were broadly distributed over anterior, central, and posterior sites, and were already present prior to the onset of the P1 component. These observations rule out an interpretation of these early effects as reflecting modulations of sensory-specific visual ERP components (P1 and N1). It is possible that the early negativity for detected-change trials as compared to undetected-change trials reflects systematic differences in observers' state of preparation between these two types of trials. When two stimuli follow each other at short and predictable intervals, a sustained negative deflection (Contingent

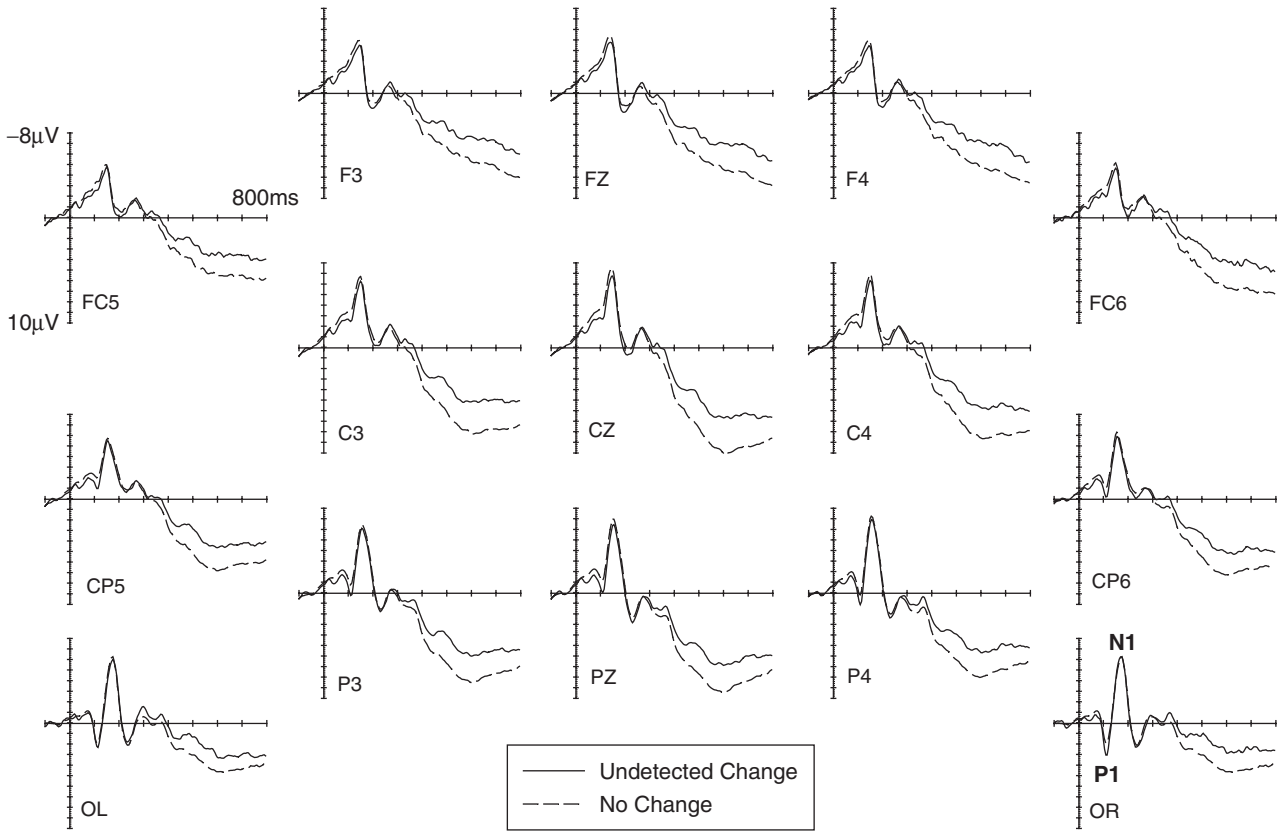

Figure 4. Grand-averaged ERP waveforms triggered in Experiment 1 in response to the second stimulus display on trials where participants reported not seeing any change (undetected-change trials, solid lines) and on trials where they correctly reported the absence of a change (no-change trials, dashed lines).

Negative Variation, CNV) is elicited in the interval between these stimuli (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). The late phase of the CNV is sensitive to stimulus anticipation and task preparation, with larger CNV amplitudes linked to more efficient anticipatory preparation (for a recent review, see Brunia, 2003). Thus, early negative amplitude modulations for detected-change trials relative to undetected-change trials might represent systematic differences in the degree of preparation between these two types of trials. Participants will have been more likely to detect the presence of a change when fully prepared and more likely to miss a change when unprepared. Consequently, the late CNV should on average be more pronounced on detected-change trials than on undetected-change trials, as was in fact found in Experiment 1.

If amplitude differences between detected-change and undetected-change trials were due to differences in task preparation, one might expect them to be already present prior to the onset of the second stimulus display. To investigate this possibility, we conducted an additional analysis on ERP waveforms elicited in response to the first stimulus array (relative to a 100-ms prestimulus baseline). Mean amplitudes obtained at midline electrodes Fz, Cz, and Pz on detected-change and undetected-change trials were compared within two successive time intervals (300–400 ms and 400–500 ms after the onset of the first stimulus array, corresponding to the final 200 ms before the second array was presented). No significant effects of change detection were found for either time window, suggesting that any CNV amplitude differences between detected- and undetected-change trials came into effect only after the second stimulus array was presented (see General Discussion for a further evaluation of this finding).

This interpretation of early ERP amplitude differences as reflecting differences in task preparation may also account for the enhanced early negativity observed for no-change relative to undetected-change trials (see Figure 4). Trials where participants missed the presence of a change (undetected-change trials) are likely to be trials where advance preparation is insufficient (see above), whereas the probability of correctly reporting the absence of a change on no-change trials should be less susceptible to variations in task preparation. Thus, ERPs for no-change trials are likely to represent a mixture of trials with high and low task preparation, and this should result in higher late CNV amplitudes relative to undetected-change trials (where mean preparation levels are assumed to be low). Because the amplitudes of these short-latency effects were small, their reliability clearly needs to be confirmed by further data. One purpose of Experiment 2 was to find out whether similar early effects could be reproduced in the context of a more difficult change detection task.

An N2pc component was triggered in Experiment 1 when participants reported being aware of a change. In contrast, this component was entirely absent on undetected-change trials (Figure 3, top), thus suggesting that the N2pc is closely linked to successful change detection. This conclusion is further supported by the fact that N2pc latency varied as a function of the speed of change detection, with earlier onset latencies for fast relative to slow detection trials (Figure 3, bottom). It is likely that this component corresponds to the enhanced posterior negativity re-

ported previously by Koivisto and Revonsuo (2003). Because these authors did not analyze their data as a function of change location, they were unable to investigate whether or not this detection-related negativity was lateralized. The N2pc is usually interpreted as an electrophysiological marker for attentional selection processes (see Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999, 2003a, 2003b). The relationship between attention, change detection, and the N2pc component will be evaluated in the General Discussion.

Finally, Experiment 1 revealed a broadly distributed enhanced positivity in the P3 latency range for detected-change as compared to undetected-change trials (see Figure 2). This finding confirms observations from previous ERP studies (Koivisto & Revonsuo, 2003; Niedeggen et al., 2001; Turatto et al., 2002). Although larger P3 amplitudes on detected-change trials have previously been directly linked to processes involved in change detection, the present results caution against such an interpretation. Larger P3 amplitudes were also observed for no-change trials relative to undetected-change trials (see Figure 4), in spite of the fact that there were no changes to be detected in these trials. One possibility is that these latter effects are due to implicit change detection (Fernandez-Duque et al., 2003; Thornton & Fernandez-Duque, 2002), although this interpretation would not account for the observation that similar P3 differences were also found between detected-change and undetected-change trials. We therefore suggest an alternative interpretation of these P3 amplitude modulations, which is able to explain both the differences observed between detected-change and undetected-change trials and between undetected-change and no-change trials. Such differences might reflect systematic variations in observers' confidence with respect to the presence versus absence of a change. Participants consistently reported that they were uncertain about the presence or absence of a change on a substantial number of trials. If they had chosen a conservative response criterion on change trials where they felt uncertain and reported the absence of a change, confidence levels should on average be lower, and decision-related processing prolonged on undetected-change trials. A temporal extension of decision-related processing is known to be accompanied by a sustained negativity in the P3 latency range, and will thus be reflected by less positive P3 amplitudes for undetected-change trials relative to detected-change trials and no-change trials.

To provide further support for this hypothesis that P3 amplitude modulations reflect variations in observers' confidence regarding the presence of a change, resulting in extended decision-related processing on undetected-change trials when confidence is low, we investigated whether P3 amplitude modulations would be found for detected-change trials as a function of response speed. On fast response trials, confidence should be high and decision processes fast, whereas on slow response trials, decision processes should be prolonged, thus resulting in a sustained negativity relative to fast response trials. An analysis of ERP mean amplitudes at midline electrodes Fz, Cz, and Pz in the P3 time range (500–700 ms poststimulus) for detected-change trials with fast and slow responses fully confirmed this prediction.[4] ERP amplitudes were more negative on slow relative to fast response trials, resulting in a main effect of response speed, $F(1,15) = 34.1$, $p < .001$.

[4]Fast and slow detection trials were classified in the same way as for the N2pc latency analysis as trials with response times within the fastest 30% or the bottom 30% of individual response time distributions.

Although this post hoc analysis provides some support for the suggestion that P3 amplitude modulations in change detection tasks are not directly linked to explicit or implicit change detection, but rather to observers' confidence, this hypothesis obviously needs to be tested more directly. This was the main purpose of Experiment 2, where participants had to rate their confidence regarding the accuracy of their perceptual judgment on every trial.

EXPERIMENT 2

Experiment 2 was designed to further explore several of the issues raised by the results of Experiment 1. Most importantly, we directly tested the hypothesis that the P3 amplitude modulations observed in Experiment 1 and in previous ERP studies of change detection primarily reflect variations in observers' confidence with respect to the presence versus absence of a change. In Experiment 2, participants were required to rate their confidence on every trial on a three-point scale (*fully confident*, *partially confident*, *not confident*). To obtain a sufficient number of change trials where confidence was low, experimental procedures were changed to make change detection more difficult. In contrast to Experiment 1, where face changes could only occur at two possible locations, there were now four possible and equiprobable change locations (see Figure 1, right side). It was expected that this manipulation would substantially decrease the percentage of detected-change relative to undetected-change trials.

If increased P3 amplitudes on detected-change relative to undetected-change trials primarily reflected variations in observers' confidence (with longer decision-related processing when confidence is low), rather than the explicit or implicit detection of a change, P3 amplitude modulations should be determined by confidence levels, and not by the presence versus absence of a change. More specifically, we predicted larger P3 amplitudes on trials where participants reported to have full confidence in their response than on trials where confidence was low, irrespective of whether a change was in fact present or not.

An additional aim of Experiment 2 was to reproduce the finding from Experiment 1 that successful change detection was accompanied by an early and broadly distributed enhanced negativity, presumably reflecting larger late CNV amplitudes related to effective task preparation. One final objective of Experiment 2 was to confirm the status of the N2pc component as an electrophysiological marker of change detection in a more difficult task.

Methods

Participants

Twenty healthy paid volunteers participated in the experiment, after giving their written informed consent. One participant was excluded due to excessive α wave activity, and 3 others were excluded because of a large number of eye movement artifacts. Thus 16 participants (6 women, 10 men, aged 21–37 years, mean age 28.5 years) remained in the sample. All participants were right-handed, and all reported normal or corrected-to-normal vision.

Stimuli, Apparatus, and Procedure

These were identical to Experiment 1, with the following exceptions. Stimulus displays again consisted of four faces, but these

were now located at the 3, 6, 9, and 12 o'clock positions at a constant distance of 4.3° from a central fixation cross (see Figure 1, right side). The experiment consisted of 12 blocks, with 60 trials per block. Intertrial interval was 1500 ms. On 20 trials per block, both displays were identical (no-change trials). On the remaining 40 trials, one of the four faces in the first display was replaced by a different face in the second display (change trials). Changes on each of the four positions occurred in a random order and with equal probability. As in Experiment 1, there was never any gender change across displays.

Participants placed their left middle finger on the left response button, their right middle finger on the right response button, and both their left and right index fingers on a third response button that was located midway between the left and right buttons, and was aligned with participants' body midline. They had to report the presence versus absence of a change by pressing the left or right response key (with response assignments again changed between blocks). Fifteen hundred milliseconds after a response was recorded, a prompt appeared on the computer screen, asking participants to rate their subjective confidence with respect to the correctness of their response (0% confident: my response was pure guess; 50% confident: my response was not pure guess, but I am uncertain whether it was correct; 100% confident: I am certain that my response was correct). Participants used the left response key to indicate their total lack of confidence, the middle key to indicate 50% confidence, and the right key to signal full confidence (100%). Training blocks consisting of 26 trials were delivered prior to the start of the first set of six experimental blocks, as well as prior to the start of the other six blocks, where response assignments were reversed.

EEG Recording and Data Analyses

These procedures were identical to Experiment 1, except for the fact that separate averages were computed for different confidence levels. Because more than half of all participants chose the 0% confidence option very infrequently, resulting in an insufficient number of epochs for EEG averaging, trials where confidence ratings were either 0% or 50% were collapsed. Thus, the factor confidence as used in all analyses only had two levels (high versus low). For change trials, averages were computed as a function of change location (left vs. right changes, collapsed across both vertical locations on the left and right sides), change detection (detected-change trials vs. undetected-change trials), and confidence (high vs. low). For no-change trials, trials with correct responses (i.e., correct rejections) were averaged separately for high- and low-confidence trials. At least 28 epochs per condition were available after artifact rejection for all participants to compute averages for high confidence and low confidence detected-change, undetected-change, and no-change trials, respectively.

Analogous to the procedures used in Experiment 1, two sets of analyses were conducted to compare (a) ERPs on detected-change versus undetected-change trials and (b) on undetected-change trials versus no-change trials. All analyses and measurement windows used were identical to Experiment 1, except that confidence (high vs. low) was entered as additional factor.

Results

Behavioral Performance

As expected, change detection performance was substantially worse than in Experiment 1. Participants correctly detected a change in the second display on only 49% of all change trials, and reported the absence of a change on 81% of all no-change trials. There was a small but significant effect of change location on hit rates, as changes on the left side were detected more frequently than changes on the right side (53% vs. 45%; $t[15] = 3.14$, $p < .01$). A signal detection analysis, where hits in response to change trials and false alarms on no-change trials were used to compute d' (see Macmillan & Creelman, 1991) resulted in an average d' of .93. This value differed significantly from zero, $t(15) = 16.4$, $p < .001$, demonstrating that change detection performance was well above chance level.

The difficulty of the change detection task was also reflected in the fact that participants reported low confidence in their perceptual judgments on more than half of all trials. Confidence was high (100%) on 47% of all change trials and on 44% of all no-change trials. As would be expected, perceptual judgments were more accurate on high-confidence trials than on low-confidence trials. Participants detected the presence of a change on 58% of all change trials where they reported to be fully confident, but only on 42% of change trials where confidence was low, and this difference was significant, $t(15) = 3.0$, $p < .01$. They correctly reported the absence of a change on 90% of all no-change trials where confidence was high, and on 73% of no-change trials where confidence was low, $t(15) = 4.4$, $p < .001$.

Reaction times ($\pm$ *SD*) were delayed on undetected-change trials (811 $\pm$ 135 ms), relative to no-change trials (796 $\pm$ 136 ms, $t[15] = 2.6$, $p < .02$). The difference between detected-change trials (831 $\pm$ 131 ms) and no-change trials approached significance, $t(15) = 1.98$, $p < .07$, whereas RTs on detected-change trials and undetected-change trials did not differ significantly. To investigate the impact of participants' confidence on reaction times, two further analyses were conducted. The first analysis compared RTs on detected-change and undetected-change trials for the factors change detection, confidence, and change location. A significant effect of confidence, $F(1,15) = 29.4$, $p < .001$, reflected the fact that RTs were faster on high-confidence trials (772 $\pm$ 127 ms) than on low-confidence trials (870 $\pm$ 139 ms). A Change Detection $\times$ Confidence interaction, $F(1,15) = 5.3$, $p < .04$, indicated that on low-confidence change trials, participants were slower to report the presence of a change than they were to (incorrectly) report its absence (891 ms vs. 850 ms, $t[15] = 2.6$, $p < .03$). The second analysis compared RTs on no-change and undetected-change trials. A main effect of presence of change, $F(1,15) = 6.9$, $p < .02$, reflecting the fact the RTs were faster on no-change relative to undetected-change trials (see above) was accompanied by a main effect of confidence, $F(1,15) = 16.2$, $p < .01$, again demonstrating that RTs on high-confidence trials (762 $\pm$ 140 ms) were faster than on low-confidence trials (845 $\pm$ 142 ms).

ERP Results: Detected-Change Trials versus Undetected-Change Trials

Figure 5 shows ERPs elicited on change trials in response to the second display, separately for trials where the change was reported (solid lines) and for trials where participants reported being unaware of a change (dashed lines). Waveforms are shown separately for electrodes contralateral and ipsilateral to the side of a change (left and right panels), as well as for midline electrodes (bottom panel), and are collapsed across high-confidence and low-confidence trials. Effects of change detection were very similar to the corresponding effects found in Experiment 1 (see Figure 2). Again, a small enhanced negativity was present for

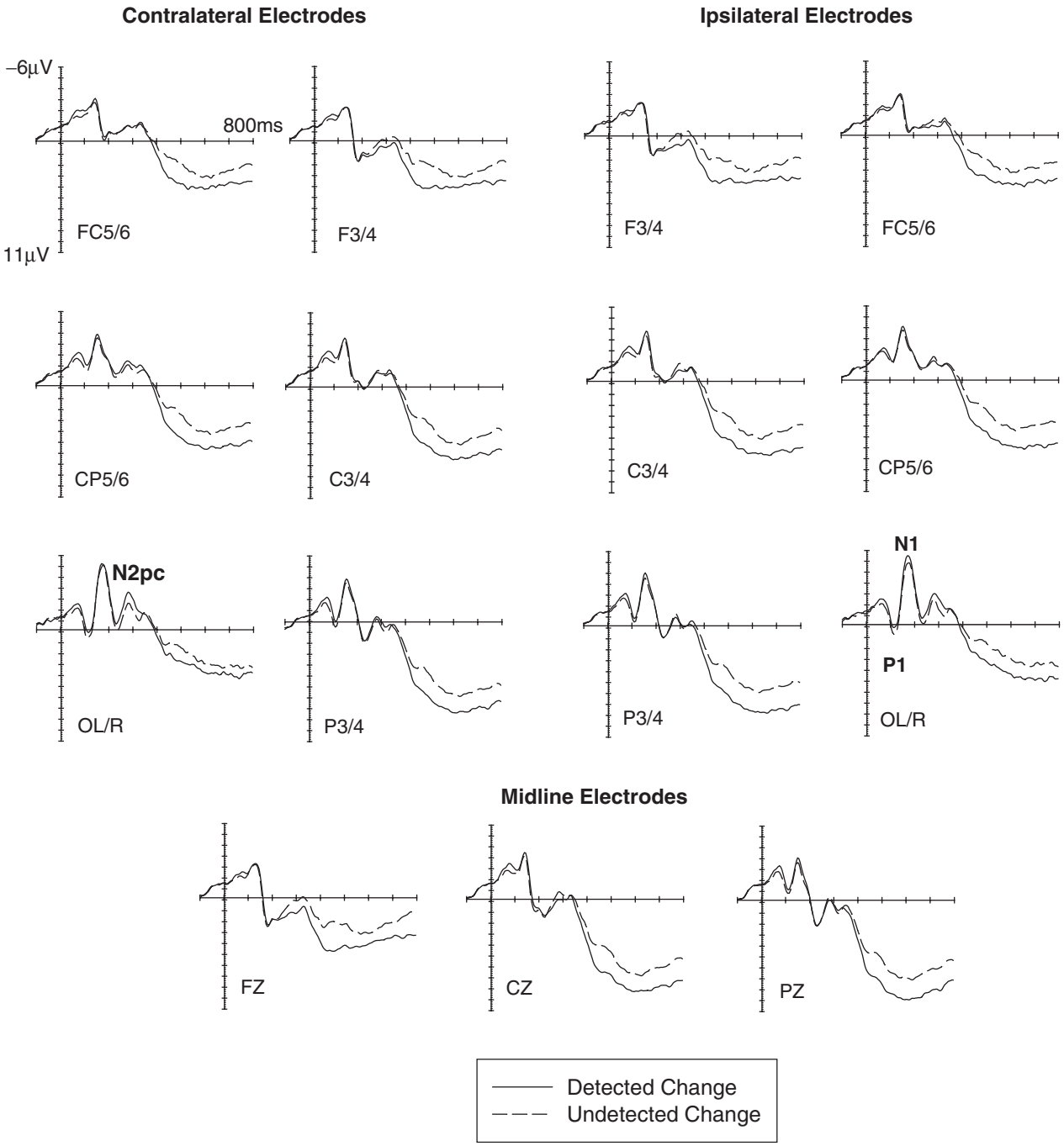

Figure 5. Grand-averaged ERP waveforms triggered in Experiment 2 on change trials in response to the second stimulus display at electrodes contralateral and ipsilateral to the side where the change occurred (left and right panels) and at midline electrodes (bottom panel). ERPs are shown separately for trials where participants reported being aware of a change (detected-change trials, solid lines) and for trials where they reported not seeing any change (undetected-change trials, dashed lines). Data are collapsed across high-confidence and low-confidence trials.

detected-change relative to undetected-change trials at very short latencies. This was followed by a posterior negativity for detected-change trials, which was most prominent contralateral to the side of the change (N2pc in Figure 5) and by a broadly distributed sustained positivity for detected-change trials relative to undetected-change trials.

As in Experiment 1, these observations were confirmed by statistical analyses. In the P1 analysis window (90–130 ms post-stimulus), a main effect of change detection was present at lateral posterior electrodes, $F(1,15) = 4.9$, $p < .05$, reflecting a larger negativity on detected-change trials. This effect approached significance at lateral central sites, $F(1,15) = 4.3$, $p < .06$. To demonstrate that this effect does not represent a genuine amplitude modulation of the P1 component, but instead a superimposed early sustained negativity on detected-change trials, an additional analysis was conducted for ERP mean amplitudes elicited be-

tween 30 ms and 80 ms poststimulus. Analogous to Experiment 1, main effects of change detection were found for all recording sites, all $F(1,15) > 4.6$, all $p < .05$, reflecting more negative amplitudes for detected-change relative to undetected-change trials (see Figure 5). In contrast to Experiment 1, no effects of change detection were present for the N1 analysis interval (160–200 ms poststimulus). Importantly, there were no main effects of confidence or any Change Detection × Confidence interactions in any of these analyses of ERPs elicited within the first 200 ms after stimulus onset, demonstrating that the early detection-related negativity was elicited irrespective of whether participants' confidence was high or low.

In the subsequent N2 analysis window (240–340 ms poststimulus), a marginally significant effect of change detection was observed at lateral posterior electrodes, $F(1,15) = 3.8$, $p < .07$. More importantly, and analogous to the results of Experiment 1, a significant three-way interaction between change detection, change location, and recording hemisphere was present, $F(1,15) = 5.0$, $p < .05$. As shown in Figure 5, an enhanced posterior N2 was elicited on detected-change trials contralateral to the side of a change (N2pc), whereas only small N2 amplitude differences were present at ipsilateral electrodes. To further confirm that the N2pc is a marker of change detection, separate analyses were conducted for detected-change and undetected-change trials. On detected-change trials, a significant Change Location × Recording Hemisphere interaction was present at lateral posterior electrodes, $F(1,15) = 13.3$, $p < .002$, reflecting the presence of the N2pc. On undetected-change trials, this interaction was entirely absent, $F < 1$, thus replicating the pattern of results obtained in Experiment 1.

Interestingly, participants' confidence in their ability to detect a change did not affect the lateral posterior N2pc component. There was neither a main effect of confidence, nor any indication of a Confidence × Change Detection × Change Detection × Recording Hemisphere interaction, both $F < 1$. To further ascertain that the N2pc was elicited regardless of whether participants' confidence was high or low, separate analyses were conducted for high-confidence and low-confidence detected-change trials. A significant Change Location × Recording Hemisphere interaction was present at lateral posterior sites for both high and low levels of confidence, both $F(1,15) > 7.3$, both $p < .02$, thus confirming that the N2pc was triggered in response to a face change irrespective of variations in observers' confidence.

In the P3 latency range (500–700 ms poststimulus), main effects of change detection were present at all recording sites, all $F(1,15) > 11.4$, all $p < .005$. A broadly distributed enhanced positivity was elicited on detected-change relative to undetected-change trials (Figure 5), again replicating the results found in Experiment 1. However, the size of this positivity in the P3 time range was strongly modulated by participants' confidence in their detection response. Effects of confidence on ERPs elicited on trials where a change was present are shown in Figure 6 for detected-change trials, and in Figure 7 (top panel) for undetected-change trials. Mean amplitudes in the P3 time window were

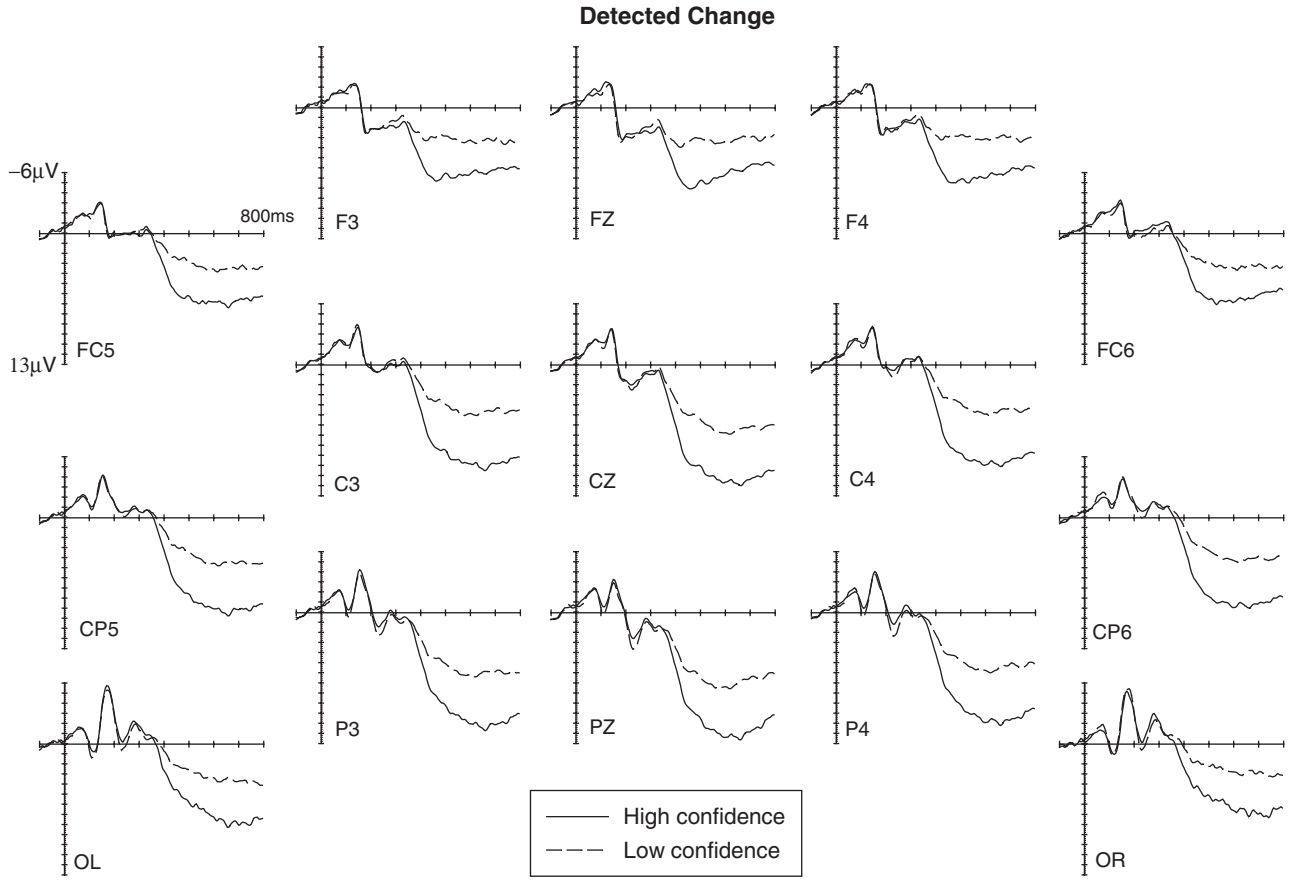

Figure 6. Grand-averaged ERP waveforms triggered in Experiment 2 on detected-change trials in response to the second stimulus display, shown separately for trials where participants were fully confident with respect to the accuracy of their detection response (high confidence, solid lines) and for trials where they were not fully confident (low confidence, dashed lines).

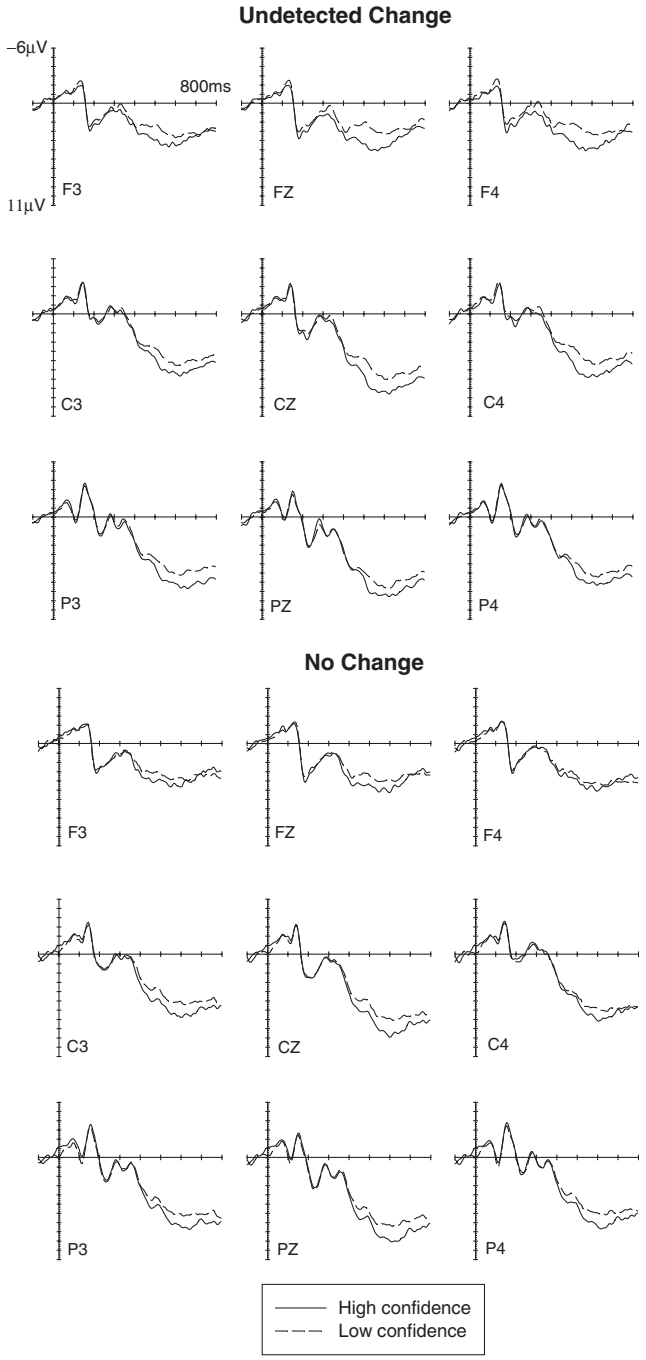

Figure 7. Grand-averaged ERP waveforms triggered in Experiment 2 on undetected-change trials (top panel) and on no-change trials (bottom panel) in response to the second stimulus display. ERPs are shown separately for trials where participants were fully confident with respect to the accuracy of their judgment that no change was present (high confidence, solid lines) and for trials where they were not fully confident (low confidence, dashed lines).

generally more positive when participants' confidence was high, and this was reflected in highly significant main effects of confidence at all electrode sites, all $F(1,15) > 47.7$, all $p < .001$. Significant Confidence × Change Detection interactions were also present at all electrodes, all $F(1,15) > 19.2$, all $p < .001$, reflecting the fact that the impact of confidence on P3 amplitudes was considerably more pronounced for detected-change trials (Figure 6) than for undetected-change trials (Figure 7, top panel). However, follow-up analyses conducted separately for detected-change and undetected-change trials revealed main effects of confidence on P3 mean amplitudes at all recording sites, not just for detected-change trials, all $F(1,15) > 75.0$, all $p < .001$, but also for undetected-change trials, all $F(1,15) > 7.2$, all $p < .02$.

The presence of Confidence × Change Detection interactions for P3 mean amplitudes could be due to the fact that effects of change detection (i.e., larger P3 amplitudes on detected-change relative to undetected-change trials) were only present when participants' confidence was high. This was confirmed in another set of follow-up analyses, which were conducted separately for high-confidence and low-confidence trials. Main effects of change detection were present for high-confidence trials at all sites, all $F(1,15) > 19.4$, all $p < .001$. In contrast, no significant P3 differences between detected-change and undetected-change trials were found at any site when participants' confidence was low.

Undetected-Change Trials versus No-Change Trials

Figure 7 shows ERPs elicited on undetected-change trials (top panel) and on no-change trials (bottom panel), separately for high-confidence and low-confidence trials. In contrast to Experiment 1, there were no effects of the factor presence of change in any analysis window. In other words, when trials were equivalent with respect to participants' perceptual reports (no change was detected), the presence versus absence of a change did not modulate ERP waveforms in Experiment 2. However, participants' subjective confidence with respect to their perceptual report did affect ERPs in the P3 time window (500–700 ms poststimulus). Main effects of confidence were present at all recording sites, all $F(1,15) > 7.0$, all $p < .02$, reflecting enhanced positivities for high- versus low-confidence trials. No Confidence × Presence of Change interactions were obtained, all $F < 1$, suggesting that confidence had similar effects on P3 mean amplitudes on undetected-change trials and on no-change trials (Figure 7). Analyses conducted separately for no-change trials only revealed significant main effects of confidence at midline electrodes and at lateral posterior sites, both $F(1,15) > 6.6$, both $p < .03$, and a nearly significant effect at lateral central electrodes, $F(1,15) = 4.2$, $p < .06$.

Discussion of Experiment 2

The primary aim of Experiment 2 was to test the interpretation of the P3 amplitude modulations observed in Experiment 1 as reflecting variations in confidence levels by asking participants to rate their confidence at the end of each trial. The increased difficulty of the change detection task relative to the first experiment (where changes could only occur at two possible locations) was reflected by the fact that detection performance was considerably worse than in Experiment 1, although still well above chance.[5] As expected, participants' performance varied as a function of their reported confidence level. Relative to low-confidence trials, responses on high-confidence trials were faster and more accurate.

[5]Participants were slightly more likely to detect changes on the left side than on the right side. This small but significant and unexpected difference might conceivably be due to a leftward visual search bias linked to reading direction, which is elicited specifically when perceptual task demands are high, as in Experiment 2.

The ERP data obtained in Experiment 2 provided clear-cut evidence against the idea that P3 amplitude modulations observed in change detection tasks directly reflect explicit or implicit change detection processes by demonstrating that these effects were determined by participants' confidence levels. Although the overall pattern found in Experiment 1 (larger P3 amplitudes for detected-change trials relative to undetected-change trials) was replicated in Experiment 2, analyses of these trials as a function of confidence revealed that this difference was exclusively caused by a particularly pronounced P3 on detected-change trials where participants declared they were fully confident in their detection response (Figure 6). This is exactly what would be predicted by the hypothesis that such P3 amplitude differences reflect the duration of change detection and subsequent decision-related processes. On average, these processes should be terminated earlier on trials where a change was present and participants were fully confident they had detected this change than on change trials where they were not confident. The fact that P3 amplitudes did not differ between detected-change trials and undetected-change trials when confidence was low further underlines that this effect is driven by confidence and not by change detection.

Differences in confidence affected P3 amplitudes on undetected-change trials and no-change trials as well, with larger P3 components when confidence was high (Figure 7). This is again in line with our duration-of-processing hypothesis, but not with accounts that attribute this effect to explicit or implicit change detection. It should be noted that high confidence resulted in larger P3 amplitudes even on undetected-change trials when participants missed the presence of a change in the second display (Figure 7, top panel), and the declared confidence in the accuracy of their judgment was obviously unwarranted. The fact that effects of confidence on P3 amplitudes were smaller for undetected-change trials and no-change trials than for detected-change trials is likely to be due to the difficulty of the change detection task. Because a changed face could be present at any of four locations, substantial processing was required to arrive at the decision that a change was absent at all of these locations. This fact can also account for the fact that, in contrast to Experiment 1 (which included only two possible change locations), there were no overall P3 amplitude differences between undetected-change trials and no-change trials.

The other results of Experiment 2 replicated and thus confirmed the findings of Experiment 1. Analogous to Experiment 1, an early negativity was observed for detected-change trials as compared to undetected-change trials. This negativity, which was tentatively interpreted as a late CNV related to effective task preparation, was most pronounced in the 30–80-ms time window, but also overlapped with the P1 component at lateral posterior electrodes. This result demonstrates that despite its small size, this early effect was replicable under conditions where task difficulty was increased. As in Experiment 1, we conducted a post hoc analysis on ERPs in response to the first stimulus array to find out whether the early negativity for detected-change trials was already present prior to the onset of the second stimulus display. No significant differences between detected-change and undetected-change trials were found for ERP mean amplitudes at Fz, Cz, and Pz in the final 200 ms prior the arrival of the second display, thus again suggesting that this effect was only triggered after the second stimulus array was presented. Experiment 2 also confirmed the status of the N2pc component as an electrophysiological correlate of change detection. As in Experiment 1, this component was elicited contralateral to the side of a change when this change was detected, but not on undetected-change trials. Interestingly, the N2pc was unaffected by participants' reported confidence in the accuracy of their change detection response.

General Discussion

The aim of the present ERP study was to uncover electrophysiological markers of change detection in two experiments where participants were presented with two successive displays containing four faces, and one of these faces could change identity across displays. Before the implications of the present results for our understanding of processes involved in change detection are evaluated, two preliminary issues need to be addressed. First, one could argue that the relatively long interval (500 ms) separating the first and second stimulus array in the present experiments might have emphasized the role of memory as compared to perceptual factors in change detection. However, visual memory is always involved in change blindness experiments when intervals beyond 80 ms are used (see Rensink et al., 1997). Under such conditions, change detection always relies on a comparison process, which depends on how many elements have been stored and how well they have been encoded. One might further argue that the interstimulus interval used here was beyond the duration of iconic memory, and that participants therefore had to use visual short-term memory to perform the task. Again, this applies equally to all change detection experiments. Iconic memory is maskable, and thus cannot be used to facilitate change detection, because the onset of the second display overwrites any previous iconic representation (Becker, Pashler, & Anstis, 2000; Landmann, Spekreijse, & Lamme, 2003). It should also be noted that intervals of 500 ms or longer have in fact been used in several other recent investigations of change detection (e.g., Beck et al., 2001; Landmann et al., 2003; Landmann, Spekreijse, & Lamme, 2004).

Another issue that needs to be addressed concerns the possible role of eye movements in the present experiments. It is conceivable that a considerable number of detected-change trials included eye movements toward the side of the change in the second display, which may not have been picked up by artifact rejection procedures. Such eye movements may have contributed to successful change detection, and therefore also to the ERP effects reported here. To demonstrate that this was not the case, Figure 8 shows grand-averaged HEOG waveforms (after artifact rejection) for Experiment 1 (left side) and Experiment 2 (right side) for detected-change trials where a change occurred in the second display on the left side (solid lines) or on the right side (dashed lines). Waveforms are shown for the 900-ms interval between the onset of the first stimulus display and the offset of the second stimulus display. Eye movements toward the right would be reflected by positive (downward-going) deflections, whereas left eye movements would be reflected by negative (upward-going) deflections. As can be seen from Figure 8, there was no indication for any tendency for eye movements toward the change location prior to and during the presentation of the second display, thus ruling out the possibility that the effects reported here were confounded by eye movement artifacts.

In both experiments, several ERP modulations turned out to be sensitive to the difference between detected-change trials, undetected-change trials, and no-change trials. A broadly distributed enhanced negativity was elicited at very short latencies on

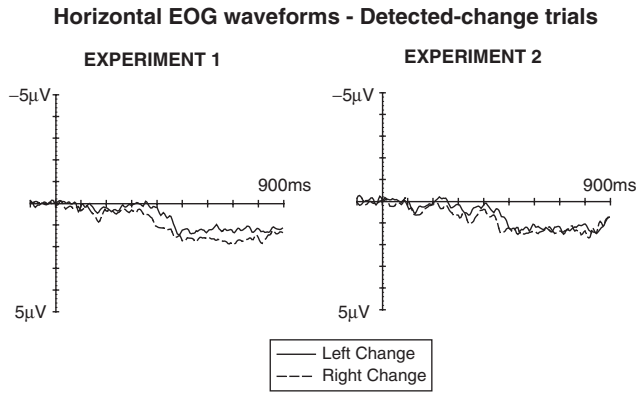

Figure 8. Grand-averaged horizontal EOG (HEOG) waveforms obtained in the 900-ms interval following the onset of the first stimulus array in Experiment 1 (left side) and Experiment 2 (right side) on detected-change trials. EOGs are displayed separately for trials where a change occurred in the second display on the left side (solid lines) or on the right side (dashed lines).

detected-change trials.[6] This effect was interpreted as reflecting the late part of the CNV (Walter et al., 1964), which is sensitive to variations in anticipatory task preparation (Brunia, 2003). Efficient task preparation, which is reflected by larger late CNV amplitudes, makes successful change detection more likely. Accordingly, enhanced early negativities were present in both experiments for detected-change trials. It is notable that in both experiments, no evidence for systematic amplitude differences between detected-change and undetected-change trials was observed prior to the onset of the second stimulus array. This negative finding might be regarded as inconsistent with our suggested interpretation of such amplitude differences as task preparation effects. However, it should be noted that in both experiments, the interval separating the two stimulus displays was always 500 ms, so that the onset time of the second stimulus was completely predictable. Under such circumstances, it is not implausible that any differential task preparation effects, as reflected by CNV amplitudes between detected-change and undetected-change trials, would be time-locked to the anticipated and fully predictable onset of the second stimulus array.

In the P3 latency range, an enhanced positivity for detected-change as compared to undetected-change trials confirms observations from previous ERP studies of change detection (Koivisto & Revonsuo, 2003; Niedeggen et al., 2001; Turatto et al., 2002). However, such P3 amplitude modulations should not be interpreted as direct electrophysiological correlates of explicit or implicit change processing. As demonstrated in Experiment 2, these modulations are determined by variations in observers' confidence with respect to their perceptual judgments, and not by change detection as such. On trials where observers are uncertain about the presence versus absence of a change, processes involved in stimulus processing and response decision take longer than on trials where confidence is high. Such prolonged processing is reflected by a sustained negativity, and thus results in a delayed and/or attenuated P3 for low-confidence relative to high-confidence trials.

The N2pc component turned out to be the most direct electrophysiological correlate of change detection. This component was elicited on detected-change trials, but was entirely absent on undetected-change trials, and its latency was linked to the speed of change detection. The N2pc has previously been observed in visual search experiments, where it was triggered contralateral to the location of task-relevant visual target stimuli (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999, 2003a). In these experiments, the N2pc was interpreted as reflecting the attentional selection of target items and/or the suppression of task-irrelevant distractor stimuli. Magnetoencephalographic (MEG) studies (Hopf et al., 2000; Hopf, Boelmans, Schoenfeld, Heinze, & Luck, 2002) have demonstrated that the N2pc reflects attentional modulations in extrastriate ventral visual cortex and in posterior parietal areas. Given its previous interpretation as an ERP marker of attentional selectivity, the new finding of the current study that the N2pc is elicited during change detection provides converging evidence for the hypothesis that change detection is closely linked to focal attention (e.g., Rensink et al., 1997; Simons, 2000).

Given the existence of such links between attention, change detection, and the N2pc component, the question needs to be raised whether the N2pc should be interpreted as a direct electrophysiological marker of conscious change detection or rather as a correlate of attentional selection processes, which are closely linked to, but still functionally distinct from, change awareness. The nature of the relationship between attention and conscious awareness has recently become a contentious issue, although it is not always clear whether the questions discussed in this context are empirical or primarily conceptual. Several authors have argued that there is no awareness of visual events beyond attention, and that visual attention and consciousness are identical (e.g., O'Regan & Noe, 2001; Posner, 1994). If this were the case, the question of whether the N2pc reflects shifts of attention toward the location of a change, or change awareness as such, might be altogether pointless. However, other authors have argued that visual consciousness and visual attention are separable phenomena (e.g., Lamme, 2003). Thus, one could assume that the N2pc reflects shifts of attention to the location of a change, and that these attention shifts are themselves caused by change detection. According to this interpretation of the present findings, the N2pc does not reflect change awareness as such, but rather the allocation of attention to task-relevant change locations. This view would be in line with recent findings by Woodman and Luck (2003b), who have demonstrated that an N2pc is elicited even when target detection is substantially impaired by object-substitution masking. These authors argue that the N2pc reflects shifts of attention to potential target locations, and that such attention shifts occur even when targets are not accessible to awareness. Clearly, the issue of whether the N2pc is directly or only indirectly (via attentional shifts) related to change awareness cannot be resolved on the basis of the present data. We thus prefer to remain agnostic with respect to the underlying fundamental question of whether attention and consciousness are identical or separable.

In summary, the present experiments have uncovered several new insights with respect to electrophysiological markers of change awareness and change processing. We have demonstrated

[6]It should be noted that a similar pattern of results (an enhanced early negativity for detected-change relative to undetected-change trials) is also apparent in the data reported in the Koivisto and Revonsuo (2003) study (see their Figure 2). However, these differences were apparently not reflected in significant effects in their analyses, which were based on peak amplitude measures (rather than mean amplitudes, as in the present study).

that the N2pc component is directly linked to the detection of change. This component could prove immensely useful in future research as a temporal marker of change detection, even in the absence of explicit task instructions and concurrent verbal reports. We have identified longer latency ERP modulations in the P3 time range, and have shown that these reflect variations in observers' confidence, rather than processes directly implicated in explicit or implicit change detection. And finally, we have identified short-latency ERP modulations, which appear to be linked to trial-by-trial fluctuations of advance task preparation, which may determine whether changes are successfully detected or not.

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