The speed of object recognition from a haptic glance: event-related potential evidence

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Recognition of an object usually involves a wide range of sensory inputs. Accumulating evidence shows that first brain responses associated with the visual discrimination of objects emerge around 150 ms, but fewer studies have been devoted to measure the first neural signature of haptic recognition. To investigate the speed of haptic processing, we recorded event-related potentials (ERPs) during a shape discrimination task without visual information. After a restricted exploratory procedure, participants \((n = 27)\) were instructed to judge whether the touched object corresponded to an expected object whose name had been previously presented in a screen. We encountered that any incongruence between the presented word and the shape of the object evoked a frontocentral negativity starting approximately at 175 ms. Using source analysis and L2 minimum norm estimation, the neural sources of this differential activity were located in higher-level somatosensory areas and prefrontal regions involved in error monitoring and cognitive control. Our findings reveal that the somatosensory system is able to complete a substantial amount of haptic processing enough to trigger conflict-related responses in medial and prefrontal cortices in less than 200 ms. The present results show that our haptic system is a fast recognition device closely interlinked with error and conflict monitoring processes.

*Keywords*: Haptics; Haptic object recognition (HOR); Tactile object recognition (TOR); Event-related potentials (ERPs); Error monitoring
INTRODUCTION

Daily actions such as switching off an alarm placed on the bedside table challenge us to discriminate objects by touch without the help of vision. Although the use of haptic information identifying objects cannot rival vision in terms of speed, there has been an intriguing debate about whether touch has a fast and viable object recognition system independent from that of vision (Amedi et al. 2001; Klatzky et al. 1987). The visual system acquires multiple types of information through parallel channels, and first brain responses associated with the visual discrimination of images arise around 150 ms (Allison et al. 1999; Thorpe et al. 1996). Somatosensory information, however, is transmitted through a network of hierarchical connections (Hyvarinen and Poranen 1978b; Iwamura and Tanaka 1978; James et al. 2007), beginning with thalamocortical circuits relaying information into the primary somatosensory cortex (SI), located in the postcentral gyrus of the parietal lobe (DiCarlo et al. 1998; Huffman and Krubitzer 2001). SI neurons project to higher-order somatosensory areas, such as the secondary somatosensory cortex (SII) and the superior parietal lobule (SPL), which compute more complex representations of shape (Roland et al. 1998). Well-defined parietal lesions have been associated with a selective disturbance in the recollection of geometrical shape, a phenomenon termed as tactile agnosia (Caselli 1991; Reed et al. 1996). In order to gather all haptic inputs together to permit object recognition, these areas are connected with the insular cortex, remote prefrontal regions and the anterior cingulate cortex (ACC) through a fronto-parietal network engaged in complex haptic object discrimination (HOR) (Binkofski et al. 1999; Stoeckel et al. 2003). Consequently, albeit touch can rapidly provide information regarding an object’s shape, it may require serial analysis as opposed to that of visual object recognition, resulting in longer response times. However, previous studies have
found shared visuo-tactile representations of shape between both modalities (Amedi et al. 2010; Lacey et al. 2009). According to these findings, the visuo-tactile region from the latero-occipital complex (LOtv) stores shape representations that are recruited both in tactile and in visual tasks. Despite this was initially interpreted as the influence of visual imagery and its interference in tactile shape discrimination tasks, it is not restricted to sighted individuals since activation in that region has also been found in congenitally blind adults.

Another aspect that has been controversial is to which extent a single grasp is sufficient for recognizing an object (Bodegard et al. 2001; Roland and Mortensen 1987; Seitz et al. 1991). To identify an object, cutaneous inputs from the skin have to be integrated with kinesthetic information from muscles and joints. A single grasp is thought to limit the amount of kinesthetic information in such a manner that disables its recognition. However, in a very interesting study Klatzky and Lederman (Klatzky and Lederman 1995) proved that a brief haptic exposure without active exploration (an ‘haptic glance’), was enough to identify an encountered object. This finding was only observed in conditions where expectancies about the object that was going to be presented were created, thus providing hypotheses about candidate objects. The ‘haptic glance’ in this experiment consisted in allowing participant's fingertips (as many as necessary) to make contact with the object for only 200 ms, avoiding to move the fingers on the object’s surface. This temporal constraint provides an initial estimate of the amount of exposure time requested for recognizing an object. In the same line, behavioral measures demonstrated that in the absence of sight, people needed less than 2 s to correctly name common objects during a free tactile exploration task (Klatzky et al. 1985). Although these studies provided an ecological benchmark of how fast and accurate our haptic system is, they did not isolate the exact time required for neural
haptic processing solely. The former focused exclusively on the time of exposure and the later, also included the time required to emit the response. Previous work in the tactile domain has analyzed the discrimination of somatosensory information using the comparison between two subsequent stimuli (Mountcastle et al. 1990; Romo and Salinas 2003). Despite that research focused in the flutter vibrations delivered to the hand (passive recognition), the procedure of the present experiment has strong similarities with the methodology used in those reports. In our study, objects were recognized via discrepancy detection between expected and actual haptic input. Noteworthy, the somatosensory information was associated to an object and active exploration was necessary to extract haptic features. The present study aimed to investigate, for the first time to our knowledge, the exact time-course of haptic recognition using fine-grained electrophysiological measures. We recorded event-related potentials (ERPs) during a HOR task in which participants were instructed to distinguish the shape of a familiar object without visual information. We found that any incongruence between the expected and the touched object elicited a frontocentral negativity starting 175 ms after the contact-time. The temporal dynamics of HOR-related selective brain signatures points to a fast specialized tactile recognition system closely linked to neural networks implicated in conflict monitoring processes.

MATERIALS AND METHODS

Participants. Twenty seven right-handed naive volunteers (11 women, mean age = 25.7 ± 7.09 years) participated in the experiment. The experiment was undertaken with the understanding and written consent of each participant, who reported no neurological or neuromuscular disorders. The study was approved by the local ethics committee in
accord with the declaration of Helsinki. One subject was excluded from the analysis due to excessive eye movement artifacts.

Haptic stimuli and procedure. Participants sat on a comfortable chair with the arm extended on a table that was (vertical distance) 35 cm below the eyes. Nine 2D wooden geometrical objects were manufactured: racket, circle, square, triangle, arrow, flower, crown, heart and lightning (Fig 1). The objects were chosen to be highly salient in order to be easily identifiable with only 3 contact points and at a single grasp. Following a pilot study with 12 shapes, 3 shapes were discarded due to difficulties in their identification. Participants were not allowed to see the objects during the entire experimental study. We obstructed vision by placing an opaque screen between the subject and the object. Prior to the experiment, participants underwent a learning-training phase to get familiar with object’s shapes. All the objects were presented for free haptic exploration until participants could discriminate all objects correctly through touch. The experimental task consisted of a constrained exploration by touching the object at three specific locations (contact points), after sliding three fingers (thumb, index and middle) through three rails that were attached to the table. Contact points were the same for each object, avoiding the use of their location to discriminate objects (Fig. 2B). Thus, the three fingers had always the same initial and final position.

At the beginning of each trial, subjects placed the right thumb, middle and index fingers in the outer edges of the rails. The name of one of the objects was displayed on a screen for 1 s, followed by a fixation cross for another 1 s. An auditory cue was then presented, indicating that the three-finger movement towards the figure could begin. The participants slid their fingers through the rails and reached the contact points (Fig. 2). In half of the trials the word displayed on the screen corresponded to the object touched (congruent), and in the other 50% of trials the object did not match the name
(incongruent). For each of the 9 objects, 8 repetitions of their congruent trial and 8 incongruent trials were presented. The incongruent trials were a combination of each shape with the remaining shapes (e.g. in the case “Circle” the 8 incongruent trials were Circle-Square, Circle-Lightning, Circle-arrow, Circle-Triangle, Circle-Crown, Circle-Flower, Circle-Heart & Circle-Racket, being the first object the one displayed in the screen and the second, the touched one). In order to obtain a high number of trials per condition for the ERP analysis, two additional series of 12 trials were included maintaining the 50% congruent and 50% incongruent proportion. In these 2 series as well as in the training phase, a random sample from all the set of possibilities was used. 3 s after the auditory cue a response prompt appeared in the screen requesting the participants to press “Yes” or “No”, considering if the object that they were touching corresponded to the name of the object previously displayed in the screen. The Yes-No choice was made by pressing one of two keyboard buttons with the left hand. The experimental session consisted of 168 trials performed in 4 different blocks, interleaved by resting periods. Two of these blocks consisted of three series of 12 trials and the other two of four series of 12 trials. Each series consisted of 6 congruent and 6 incongruent trials randomly presented. The total duration of the experiment was 80 min. Finger movements were recorded using an infrared motion capture system (CMS-30P, Zebris, Isny, Germany) with a sampling frequency of 83 Hz and a spatial resolution of 0.1 mm. Three sensors were attached to the three fingers of the subject’s right hand to measure the time at which subjects reached the object (contact time). Data recording began 100 ms before the auditory cue and ended 3 s after.

**Behavioral analysis.** To address whether the chosen set of shapes was appropriate for the task, differences in objects’ discriminability were analyzed by an ANOVA on the discriminability index (d’) with the presented shape as a factor. The discriminability
index is defined as the probability of a hit minus the probability of a false alarm (Hit: respond yes when the correct response is yes; FA: respond yes when the correct response is no). The higher the $d'$, the easier was to recognize the object. In case the discriminability differed depending on the shape, Bonferroni-corrected pairwise t-tests were used to determine which pair of objects showed discriminability differences. Contact-time (CT) was defined as the time when the absolute velocity of the last finger reaching the object was lower than 5% of its peak velocity. Other criteria for defining CT were also considered but finally rejected: A fixed velocity threshold was discarded due to high inter-trial variability of velocity, and a varying threshold corresponding to 5% of the average peak velocity between fingers was rejected due to inter-finger speed variability. Response-time was defined as the time needed to answer the Yes-No question. To note, the response time in the present study is not truly informative of the speed of the tactile discrimination process as we requested participants to delay 3 s their motor response in order to avoid contamination of the EEG signal from ERP-motor related components. Trials with an incorrect Yes-No response (incorrect trials) or with a response-time higher than 2 s were removed from the analysis. The rejection rate was 11% and did not differ between congruency conditions ($p = 0.57$).

**EEG recordings and analysis.** The electroencephalogram (EEG) was recorded from 29 electrodes in an electro-cap (Electro-Cap, International) using Brain Vision Recorder software (Version 1.3, Brainproducts, Munich, Germany). Electrode positions were based on the standard 10/20 positions (Jasper 1958): Fp1/2, Fz, F7/8, F3/4, Fcz, Fc1/2, Fc5/6, Cz, C3/4, T7/8, Cpl/2, Cp5/6, Pz, P3/4, P7/P8, PO1/2, Oz. Eye movements and blinks were monitored by electrodes placed on the external canthus and the infraorbital ridge of the right eye. All scalp electrodes were referenced offline to the average of the reference electrodes, placed at the right and left mastoid. Electrode impedances were
kept below 5kΩ. The EEG signal was sampled at 250 Hz and filtered with a band-pass of 0.01–70 Hz (half-amplitude cutoffs). Trials with base-to-peak electrooculogram (EOG) amplitude of more than 75 μV, amplifier saturation, or a baseline shift exceeding 200 μV s⁻¹ were automatically rejected (Cunillera et al. 2008).

Contact-locked ERPs for artifact-free trials were averaged over epochs of 900 ms, including a 100 ms pre-stimulus baseline. In order to obtain reliable averages we required each condition to have a minimum of 60 trials per participant. We submitted amplitude values to repeated measures ANOVA that included two within-subjects factors: Congruency (congruent vs. incongruent) and Electrode (29 levels). In case an effect of Electrode or a significant Congruency x Electrode interaction was found, we further decomposed by selecting 15 electrodes for a topographical analysis according to two factors (Cunillera et al., 2006): Laterality [3 levels: left (F3, Fc1, C3, P3, PO1), central (Fz, Fcz, Cz, Pz, Oz) and right (F4, Fc2, C4, P4, PO2)] and Anterior-posterior [5 levels: frontal (F3, Fz, F4), fronto-central (Fc1, Fcz, Fc2), central (C3, Cz, C4), parietal (P3, Pz, P4) and parieto-occipital (PO1, Pz, PO2)]. This analysis was carried out on data corrected using the vector normalization procedure (McCarthy and Wood 1985). Post-hoc analyses were performed when appropriate. The onset and offset latencies of the congruency effect for each electrode were determined via a stepwise series of one-tailed serial t-tests (step size = 4 ms) and defined as the point at which ten consecutive t-tests showed a significant difference from zero ($t = 2.056$) (Rodriguez-Fornells et al. 2002). Greenhouse–Geisser epsilon was applied when the assumption of sphericity was not met (Jennings and Wood 1976).

To derive a topographical visualization of the somatosensory processing voltage sources, we transformed all the contact-locked averaged ERP waveforms into reference-
free current source density (CSD) estimates (μV cm\(^{-2}\) units, head radius=10 cm) (Perrin et al. 1989).

**Source localization analysis.** Brain Electric Source Analysis (BESA 2000 version 5.3 (Scherg 1990)) was used to estimate the cortical areas involved in haptic processing. The L2 minimum-norm estimation (Hamalainen and Ilmoniemi 1994) was applied for source reconstruction. We used an idealized three-shell spherical head model (radius = 85 mm). The minimum-norm was applied to the data across the latency interval in which the difference between correct and incorrect trials was statistically significant (172-456 ms). Spatio-temporal weighting was applied to the data using the signal subspace correlation method of (Mosher and Leahy 1998). The BESA algorithm also computed the location and the orientation of multiple equivalent dipolar sources by calculating the voltage scalp distribution that would be produced for a given dipole model (forward solution) and comparing it with the original scalp distribution. The congruent-incongruent difference waveform was analyzed. Following previous solutions to the neural sources of somatosensory processing (Reed et al. 2004), two single dipoles were fitted in the ACC and SII respectively, and two symmetrical dipoles were subsequently fitted near the posterior bank of the inferior frontal gyrus (IFG). Source analysis was performed for the interval in which the difference between congruent and incongruent trials was statistically significant (172-456 ms). The final locations of each dipole were projected on mean structural T1 MRI images of 24 individuals and converted into Talairach coordinates (Talairach and Tournoux 1988). The latencies of major peaks in the dipole source waveforms were taken as indices of neural response timing. Each symmetric dipole pair was constrained to be mirror-image in location only.
RESULTS

Behavioral analysis

The results on the discriminability index suggest that the difficulty to recognize the objects differed across shapes ($F(5,125)=2.5$, $p = 0.03$). The ‘flower’ shape seemed to be the most difficult object to discriminate, since the only pairs (from all 72 possible pairs) that differed on the discriminability index were flower-arrow ($t(25)= - 4.0$, $p = 0.04$) and flower-circle ($t(25)=- 3.6$, $p = 0.04$). The mean percentage of correct responses was 94.4% (SD = 3.6), denoting a remarkably good performance. The mean overall contact time (or duration of the movement -time between the onset of the movement towards the object and the contact with it-) was 551.9 ± 176 ms. The mean response time was 496 ± 102 ms.

ERP results

We inspected the grand average ERPs waves of all scalp electrodes from 100 ms pre-stimulus to 800 ms post-stimulus for congruent and incongruent conditions. The incongruence between the touched object and the observed word elicited a prominent negativity ($F(1,26) = 18.5$, $p < 0.001$) arising around 170-180 until 450 ms (Fig. 3A). The analysis showed a significant Congruency x Electrode interaction ($F(28,728) = 8.3$, $p < 0.001$), indicating differences in the topographical distribution of the congruency effect. Decomposition of this interaction revealed that the congruency effect was modulated as a function of the laterality (Congruency x Laterality, $F(2,52) = 19.8$, $p < 0.001$), a modulation that was different across the sagittal axis (Congruency x Laterality x Anterior-Posterior, $F(28,208) = 7.5$, $p < 0.001$). Post-hoc contrasts indicated that the
congruency effect was maximum in midline central and midline fronto-central sites (C3, 
$t(26) = 3.2, p = 0.004$; Cz, $t(26) = 5.2, p < 0.001$; C4, $t(26) = 5.0, p < 0.001$; Fc1, $t(26) = 
3.8, p = 0.001$; Fcz, $t(26) = 4.4, p < 0.001$; Fc2, $t(26) = 4.6, p < 0.001$). The left panel of Fig. 3B reflects the time-course of activation in the midline-central site that was found to contribute more to the congruency effect (Cz location). We observed that the incongruence between the touched object and the observed name elicited a negativity starting at $172 \text{ ms}$. One-tailed serial t-tests revealed that the effect peaked at $300 \text{ ms}$ and lasted until $456 \text{ ms}$ (Fig. 3C). The 3D isovoltage topographical mapping illustrates the distribution of the congruency effect (Fig. 4A). CSD maps precisely localized the voltage source locations, which revealed a differential morphology in central and frontal sites (Fig. 4B). Post-hoc comparisons between Congruent and Incongruent CSD estimates reported a higher activity in Cz ($t(26) = 4.7, p < 0.001$), F7 ($t(26) = -3.0, p = 0.005$) and Fcz ($t(26) = 2.9, p = 0.007$) when the word and the expected object did not match.

Source analysis

Source reconstruction using minimum-norm maps suggested a frontal and central pattern for differential processing between congruency conditions (Fig. 4C). The strongest activation is limited to a 250-350 ms time window over frontal and pre-frontal regions. The dipole solution identified the possible neural generators of the different neural activity in the incongruent condition. Fronto-central negativity was explained by a four-source model with one single ACC dipole, one single dipole in the contralateral SII and two symmetrical sources situated in left/right IFG (Fig. 5). This four-source model explained up to 90% (Resting Variance = 9.13%) of the variance within the time interval where congruent and incongruent ERP waveforms statistically differed (172-
456 ms). Source waveforms of the SII dipole showed a shorter peak-latency at 240 ms, whereas the ACC and IFG peaked around 300 and 350 ms, respectively.

DISCUSSION

The present study sought to examine the time-course of the neural correlates underlying haptic recognition of objects. We demonstrated that shape identification of an unexpected object elicited an increase of neural activity in frontocentral regions around 175 ms after contact-time. Moreover, SII and IFG in conjunction with the ACC seem to be the neural generators of this differential activity, supporting their crucial role in the fast detection of conflicting stimuli. Our results reveal a substantial deal of haptic processing accomplished before 200 ms, including the neural processes required to trigger neural networks involved in error monitoring and conflict detection.

Our study provides further evidence that object identification is possible at a single grasp (similarly as reported by Klatzky and Lederman 1995), when expectancies about the object that is going to be touched are created. Precisely, our results indicate that a restricted exploratory procedure that prevents the extraction of global volumetric attributes of an object (the most fundamental information needed for identification) is sufficient to enable the recognition of objects that differ only on their shape. Noteworthy, the chosen set of shapes showed no differences in their discriminability, except for 2 of the 72 possible pairs. In order to create a sensory expectancy, participants had first to associate the displayed name with an object (categorization), and then make use of working memory mechanisms to retrieve and maintain the representation of the object or concept until reaching the presented shape. The haptic
processing of the presented shape could then begin. Haptic inputs travel in a hierarchical
fashion from the periphery to different subdivisions of SI [including Brodmann’s areas
(BA) 1, 2, 3a and 3b (Bodegard et al. 2001; Iwamura 1998)]. However, Brodmann’s
areas (BA) 1 and 2 also receive input from neurons located in BA3a and BA3b,
suggesting that areas 1 and 2 may actually represent a higher stage in haptic processing
(Hyvarinen and Poranen 1978a; Iwamura and Tanaka 1978). Information is then
projected to SII and other interconnected areas separate from the somatosensory cortex
(such as the SPL or the intra parietal sulcus), which are involved in integrating low-
level haptic inputs as well as somatosensory and motor information and compute more
complex representations (Bodegard et al. 2000; Roland et al. 1998). In our task, when
the object representation had been completed, the discrimination process could start.
The working memory representation had to be compared with the actual perception.
Lastly, the decision outcome, presumably involving cognitive control and error
monitoring processes, had to be kept in the working memory for nearly 2 sec before
executing the decision (‘Yes-No’ choice). As a result, a type of conflict-related
negativity was elicited following the trials with a mismatch between the expected and
the actual input. Interestingly, our source reconstruction analysis results showed that
contralateral SII was more active retrieving shape information from incongruent objects,
corroborating its importance in the fast coding of complex macrorgeometrical attributes
during shape discrimination. This concurs with previous studies reporting an increase in
SII activity during complex object manipulation (Binkofski et al. 1999), and points to
SII as a key player integrating somatosensory inputs to generate a coherent
representation of an object, rather than the distinction of specific object features
(Sinclair and Burton 1993). In agreement with this view, seminal studies in monkeys
and humans reported that SII lesions produced severe deficits in TOR tasks concerning
the retention of shapes (Caselli 1991), without loss of simple tactile sensation or motor control (Ridley and Ettlinger 1976).

While the abovementioned evidences speak to the importance of somatosensory cortices for haptic processing, further areas related to short-term information storage, retrieval, comparison, and decision making are necessary for fast sequential haptic discrimination (Stoeckel et al. 2003). A particularly compelling example corresponds to the existence of a frontoparietal network involved in object manipulation: tract-tracing studies showed cortico-cortical connections of the prefrontal cortex with the somatosensory cortex (Preuss and Goldman-Rakic 1989), which contributed to the gating of haptic information (Yamaguchi and Knight 1990). In addition, cortical projections from the SII to motor-related areas may indicate that SII provides somatosensory feedback gained from exploration of the manipulatory movements necessary to extract salient object information (Friedman et al. 1986; Reed et al. 2004). These neural networks might provide potential pathways for top-down modulation of somatosensory areas (Gogulski et al. 2013). In this regard, we found that unexpected geometrical properties were able to trigger a network of neural generators which has been previously associated or conflict monitoring and further cognitive control processes (Botvinick et al. 2001; Marco-Pallares et al. 2008). Therefore, our results support fast somatosensory projections to frontal and prefrontal regions, sending shape representations to supramodal cognitive processes. Specifically, shape processing of an incongruent object elicited an increase of neural activity 300 ms after touching the object in the ACC, which has been largely proposed to play a prominent role in conflict monitoring (Botvinick et al. 2004; Dehaene et al. 1994; Ridderinkhof et al. 2004). This finding suggests that incongruent-related activity is consistent with error-related components sensitive to erroneous somatosensory information, such as the error-related
negativity (ERN) (Holroyd et al. 1998) or conflict monitoring brain signatures (Rodriguez-Fornells et al. 2002). Importantly, the ACC was also found to be the neural generator in an ERP study following incorrect tactile feedback (Miltner et al. 1997). Subsequently, our data revealed a possible influence of IFG approximately 350 ms after contact-time. Our results concur with previous neuroimaging studies that implicated IFG in complex haptic discrimination (Binkofski et al. 1999; Stoeckel et al. 2003). This source reconstruction is also in accordance with prior studies that posited IFG and surrounding insular cortex as neural sources of cognitive control, with these regions being highly interconnected with the error and conflict monitoring system (Donamayor et al. 2012; Gehring and Knight 2000).

The present insights on the temporal dynamics of HOR neural correlates have a number of important implications. First, they outline a fast stream of the haptic system capable of generating neural signatures of efficient haptic discrimination in less than 200 ms. Second, they link the wealth of literature about complex haptic processing in higher-order somatosensory areas with error and conflict monitoring networks. In particular, they reconcile the observation that medial frontal and lateral prefrontal areas inspect the reliability of sensory information from different modalities throughout top-down modulations. That being said, further evidence from connectivity approaches will be needed to make strong claims about the specificity of the processes taking place in each step of the modeled network and their directionality.

REFERENCES


FIGURE CAPTIONS

Figure 1. Each stimulus (racket, circle, square, triangle, arrow, flower, crown, heart and lightning) with its 3 contact points.

Figure 2. A. Time-course of a trial procedure, including the duration of each element. B. Schematic illustration of the contact-points in two objects (circle and triangle). Solid lines corresponded to the three rails that were used as guides in order to reach the object. The initial position of the fingers is indicated by the red squares and the final position (contact points) by the black circles. Lower panel illustrates the overlap of both figures, confirming that objects were chosen as a means to have the same contact point.

Figure 3. A. Grand-average (N = 27) contact-locked ERP waveforms for Congruent and Incongruent conditions (dashed and dotted lines) and their respective difference waveform (solid line). The grey area indicates the time interval where the two conditions differed statistically. B. Cz difference waveform and t-value evolution (C). Grey dotted line indicates the latency (172 ms) at which significance is reached (t-value = 2.056).

Figure 4. 3D isovoltage topographical mapping of temporal evolution of the congruency effect. (A) Spatial distribution of differential voltage (Incongruent - Congruent) every 50 ms in the 200-400 ms time-window. (B) Scalp distribution of CSD difference waveform and (C) Minimum-Norm estimates.

Figure 5. Dipole model for the neural sources of the (Incongruent – Congruent) ERP difference waveform. Both left SII dipole (pink; x = -45.6, y = -20.9, z = 19.8) and ACC dipole (red; x = -0.7, y = 4.3, z = 49.5) together with symmetric dipoles at IFG (green and blue; x = ±44.2, y = 23.2, z = 5.3) were fit over the 172–456 ms interval. Time-course of each computed dipole is represented in the source waveform. Images on the right side show the anatomical location of each dipole.
A. 

Incongruent

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Incong - Congruent

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Fc1 Fcz Fc2

Cz C4 C3

Cp1 Cp2

m

V

5

10

-5

400 800

Time (ms)

7

-7

800 ms

B.

(EEG traces and t-value graph)

-5

5

10

μV

800 ms

(EEG traces and t-value graph)

7

2

300

172 456 800 ms