

Cortical processing of near-threshold tactile stimuli: An MEG study

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Abstract

In the present study we tested the applicability of a paired-stimulus paradigm for the investigation of near-threshold (NT) stimulus processing in the somatosensory system using magnetoencephalography. Cortical processing of the NT stimuli was studied indirectly by investigating the impact of NT stimuli on the source activity of succeeding supra-threshold test stimuli. We hypothesized that cortical responses evoked by test stimuli are reduced due to the pre-activation of the same finger representation by the preceding NT stimulus. We observed attenuation of the magnetic responses in the secondary somatosensory (SII) cortex, with stronger decreases for perceived than for missed NT stimuli. Our data suggest that processing in the primary somatosensory cortex including recovery lasts for <200 ms. Conversely, the occupancy of SII lasts ≥ 500 ms, which points to its role in temporal integration and conscious perception of sensory input.

Descriptors: Sensation/perception, Normal volunteers, MEG

Tactile stimulation near or below the perceptual threshold is—in addition to clearly detectable above-threshold stimuli—a useful tool to study the neural mechanisms of information processing in the somatosensory system. Studying a sensory system at its threshold provides the likelihood to disclose features that might remain unseen during above-threshold stimulation. For example, differences in cortical responses between near- and supra-threshold stimuli could provide further insight into the neuronal mechanisms that enable the somatosensory system to process a wide dynamic range of stimulus intensities. Additionally, differences in brain responses for perceived and missed near-threshold stimuli might elucidate the neurophysiological basis of conscious perception. However, the amplitude of somatosensory evoked responses is known to be modulated by the intensity of the stimulation (Jousmäki & Forss, 1998; Torquati et al., 2002), with weak cortical responses for near-threshold stimuli and larger responses for higher intensities. Therefore, the investigation of cortical processing following near-threshold tactile stimulation is rather intricate.

To date, little is known about the cortical processing of somatosensory stimuli that are not consciously perceived—how far they are processed in the brain and what aspects of cortical re-

sponses are modulated by the reduction of stimulus intensity below the perceptual threshold.

In a series of psychophysical experiments, Schweizer, Maier, Braun, and Birbaumer (2000) and Schweizer, Braun, Fromm, Wilms, and Birbaumer (2001) studied localization errors of non-consciously perceived tactile stimuli with intensities below the perceptual threshold that are mislocalized to fingers other than the ones stimulated. Interestingly, the distribution of mislocalizations across fingers deviated from a chance distribution, showing a higher frequency of mislocalizations to the fingers neighboring the stimulated fingers than to the more distant ones. Schweizer et al. (2000, 2001) concluded that even for near-threshold stimuli that cannot be correctly localized to the stimulated finger, participants still had access to some information about the stimulus location, albeit with a lower spatial resolution than for clearly detectable stimuli. One might conclude that the observed distribution of mislocalizations across fingers arises from weaker contrast enhancement of cortical activation for below-threshold than for suprathreshold stimuli.

The present study was designed to demonstrate the applicability of a paired-stimulus paradigm for the investigation of near-threshold stimulus processing in somatosensory cortices by the use of magnetoencephalography. In this indirect approach, we studied the impact of near-threshold prime stimulus on a subsequent above-threshold test stimulus. On the basis of previous studies that report the attenuation of cortical responses within pairs of clearly perceptible above-threshold stimuli (Hamada,

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Kado, & Suzuki, 2001; Wikström et al., 1996), we hypothesized that the responses in somatosensory cortical areas evoked by test stimuli are reduced because of preceding prime stimuli even if they are presented with intensities near the perceptual threshold. The duration of this attenuation effect has been regarded as the lifetime of sensory memory in cortical areas, which relates to the functional aspect of evoked responses (Hamada, Otsuka, Okamoto, & Suzuki, 2002). If stimulus information is encoded in the neuronal response of an assembly of neurons, similar assemblies would be activated by the prime and test stimuli. However, if the neuronal assembly preactivated by the prime stimulus is not fully recovered yet, it cannot be entirely reactivated by the test stimulus, resulting in a reduced response to the test stimulus. Hence, the extent and duration of amplitude reduction can be seen as an indirect measure for prime stimulus processing in somatosensory cortical areas.

The paired-stimulus paradigm was applied in two experiments. In the first experiment, stimulus pairs were presented with an interstimulus interval (ISI) of 300 ms to test the general applicability of the paradigm for the investigation of near-threshold processing in primary (SI) and secondary (SII) somatosensory cortex by means of the differences in cortical responses due to conscious perception of the stimuli. We hypothesized that even the weak cortical activation evoked by near-threshold stimuli would reduce the amplitude of SI and SII responses to the subsequent test stimulus, with a stronger reduction for near-threshold stimuli that are consciously perceived. Additionally, two control conditions were applied. The first control condition represented the maximal response that could be expected for the test stimuli by using a sham prime stimulus. The second control condition was intended to obtain the minimal response for the test stimulus inducing a maximal effect of amplitude reduction by the prime stimulus (prime stimulus at maximum intensity).

Assuming that the amplitude reduction depends on the processing status of the prime stimulus, it could be expected that the extent of amplitude reduction strongly depends on the duration of the interstimulus interval. Because of this, in the second experiment, with another group of participants, we presented stimulus pairs with ISIs ranging from 150 ms to 450 ms. By varying the ISIs between prime and test stimulus, we intended to (1) replicate the findings of amplitude reduction in Experiment 1 and (2) determine the ISI with the best effects in amplitude reduction, those being the most suitable to study further aspects of near-threshold stimulus processing with this paradigm. Making use of the high temporal resolution of MEG, we wanted to (3) determine the temporal characteristics of amplitude reduction due to previous stimulation and (4) determine the SI responses for the amplitude reductions in stimulus pairs with the shortest ISI of 150 ms. We hypothesized that the cortical responses in SII would be reduced by the preceding near-threshold stimuli for either of the ISIs, with weaker amplitude reductions for the longest ISI of 450 ms. Furthermore, we expected that for the shortest ISI of 150 ms, SI responses would also be reduced due to the preceding prime stimulus.

EXPERIMENT 1

For the initial testing of the paired-stimulus paradigm, stimulus pairs were presented with an ISI of 300 ms between the prime and the test stimulus. We hypothesized that cortical responses to the

test stimuli would be reduced due to the preactivation of the same finger representation in somatosensory cortical areas by a preceding near-threshold stimulus. Stronger effects of amplitude reduction were expected for the near-threshold stimuli that are consciously perceived. To explore the feasibility of using paired-pulse stimulation, an ISI of 300 ms was chosen in the first experiment, which minimized the overlap of evoked responses to the prime and test stimuli while it retained the possibility of observing the interaction between the prime and the test stimuli.

Methods

Participants

Fourteen healthy right-handed volunteers (11 women and 3 men; mean age \pm standard deviation: 23.14 ± 3.78 years, range 18–32 years) participated in the study after having given informed consent. All participants were right-handed as assessed by the Edinburgh Inventory (Oldfield, 1971). The experimental procedure had been approved by the ethics committee of the Medical Faculty of the University of Tübingen and was conducted in conformance with the Declaration of Helsinki. Participants were seated comfortably on a height-adjustable chair inside a magnetically shielded room (Vakuumschmelze, Hanau, Germany) with their head fixed with cushions and a chin rest in the mold of the dewar of the 151-channel whole-head magnetoencephalography system (VSM Medtech, Vancouver, Canada). The participants were instructed to gaze at a fixation cross on a screen in front of them and to report the number of tactile stimuli presented in each trial. To avoid additional auditory and visual information about the stimulus, white noise was presented via ear plugs and the participant's left hand with the tactile stimulator attached was covered with a blanket.

Stimulation

During neuromagnetic recordings, participants received either pairs of short tactile stimuli or a single suprathreshold stimulus (sham condition) to their left index finger delivered by a piezoelectric stimulator. The stimulus pairs consisted of a prime stimulus, varying in intensity (near-threshold or suprathreshold stimulation) on a trial-by-trial basis, followed by a suprathreshold test stimulus, which was presented at the maximum intensity of the tactile stimulator. In the sham condition, only the test stimulus was applied. The prime stimulus was a sham stimulus with zero intensity that only activated a piezo crystal without protruding the stimulation rod to the skin, thus generating the same clicking noise as the other stimuli. Before the recordings, participants were informed that either one or two stimuli would be presented per trial. They were instructed to report the number of stimuli by pressing one of two buttons that were mounted on the right armrest of the chair.

According to the intensity of the prime stimulus, trials were classified as having the following conditions: sham (sham stimulation with zero intensity), NT (near-threshold intensity), or max (maximum intensity). The group of NT trials was further subdivided pursuant to the participants' response in the BT (prime stimulus below the perceptual threshold; only one stimulus perceived) or AT (prime stimulus above the perceptual threshold; prime and test stimuli perceived) condition.

The sham condition with one stimulus and the max condition with two stimuli presented at maximum intensity served as the control conditions. The sham condition represented the maximum cortical response to the test stimulus without the impact of

the preceding prime stimuli. Therefore, the amplitudes of the evoked response to the test stimulus in the sham condition served as reference for comparison to the cortical responses evoked by the test stimuli in the other conditions. The maximum effect of amplitude reduction was explored in the max condition. The amplitudes of the evoked responses for the test stimuli after the application of a near-threshold prime stimulus were assumed to range between the amplitudes obtained in the sham and the max conditions. In case the near-threshold stimuli were not to have an effect on the test stimulus responses, it would remain unclear whether the paired-stimulus paradigm could disclose any interaction of two subsequently presented stimuli or whether the intensity of the prime stimulus was just too weak. Applying the max condition could verify which of the explanations was true and could clarify the applicability of the paired-stimulus paradigm.

Concerning the behavioral data, the percentages of correct responses in the control conditions served as an indicator for the participant's vigilance during the recordings. Verifying the hit rates in the sham and max conditions assured that participants were alert and dutifully responded to the task.

The tactile stimuli were short, nonpainful pulses (50 ms, half a cycle of a sine wave) that were presented to the participants' left index finger with a stimulation unit based on commercially available display elements for Braille letters (Metec AG, Stuttgart, Germany). These Braille elements typically consist of eight rods arranged in a 2×4 matrix that can be individually protruded by the activation of piezo-crystals. The four center rods were protruded simultaneously during stimulation in order to compensate for slight shifts of the finger during the experiment. The participants placed their left index finger on the contact area of the stimulator. The stimulation rods only touched the skin during stimulus presentation and were otherwise hidden below the contact area. Because of the presentation of a sine wave stimulus, the maximum rod protrusion was reached after a delay of ~ 25 ms.

The stimulus intensity of the prime stimuli was realized by means of the extent of rod protrusion (maximum 1 mm). For near-threshold stimuli, an intensity level of 10% of the maximum protrusion was applied for the first stimulus. In the following trials, the intensity was adapted throughout the measurement according to a simple 1 up–1 down staircase procedure (step size: 1%), based on the participant's response in individual trials. In the case of near-threshold stimulus detection, the intensity was reduced by one step. If the participant only perceived the test stimulus in NT trials, the stimulus intensity was increased by one step. Using this adaptive procedure, a counterbalanced number of BT and AT trials was obtained. Before the first recording session, participants performed 50 training trials that were not included in data analysis but were used to adapt the near-threshold stimulus intensity to the individual threshold.

Each trial consisted of a stimulation phase and a subsequent response phase (Figure 1). Visual cues ($\sim 1^\circ$ of visual angle) that were displayed on a screen in front of the participants (distance of participant to screen: 1 m) signaled the beginning and end of each stimulation phase. Before each trial, the cue was a gray "x" that switched to a "+" 500 ms before the onset of the prime stimulus and thereby signaled the beginning of the stimulation phase. Then, depending on the stimulation condition, one or two tactile stimuli were presented to the participant's left index finger. Stimuli were separated in time by an ISI of 300 ms. Participants had to wait for the visual cue to switch back to the "x" (400 ms

after the offset of the test stimulus) before they were allowed to respond. After the response had been entered or the response time of 1.6 s had elapsed, the next stimulus pair was presented after an intertrial delay ranging from 0.7 to 1 s.

The experiment comprised four recording sessions (9 min each) per participant. To obtain a sufficient number of trials per condition, the same task was repeated in all four recordings with 200 trials each. In each experimental block, all conditions were presented in a random order. NT trials were presented twice as often as trials of the two control conditions (sham and max), because trials of the NT condition were subcategorized after the recordings. Therefore, recordings resulted in a total number of 200 trials for the sham and max conditions and 400 trials for the NT condition (approximately 200 BT and 200 AT trials).

Recordings

Magnetic brain responses were recorded continuously for 540 s per recording session with the 151-channel whole-head magnetoencephalography system. The MEG signal was digitized at 625 Hz using a low-pass anti-aliasing filter of 208 Hz. The continuous recording was filtered off-line with a 40-Hz low-pass filter and a 1-Hz high-pass filter and segmented into trials of 2.55 s. Each segment included the neuromagnetic responses evoked by the tactile stimuli and the visual cues as well as a prestimulus baseline of 250 ms that was set before the first visual cue of each trial, that is, 750 ms before the first tactile stimulus.

Data Analysis

Behavioral data. To control for simple guessing or inattentiveness during the recordings, the percentage of correct responses for the two control conditions (sham and max) as well as the number of BT and AT trials for the NT condition were calculated. Furthermore, the mean intensity and the variance of near-threshold stimuli in the AT and BT trials were calculated for individual participants. In an *F* test, the difference of mean stimulus intensities for AT and BT trials was compared to the overall variance of intensities for each experimental block and individual participant in order to determine whether the near-threshold stimuli in AT and BT trials were within the same range of the overall intensity variation.

Somatosensory evoked responses. Data analysis focused on changes in neuromagnetic responses evoked by the test stimulus according to the intensity and perception of the preceding prime stimulus. In general, somatosensory stimuli above the perceptual threshold elicit responses from contralateral SI and bilateral SII. Electric stimulation of the median nerve generally elicits early responses peaking at ~ 20 ms and ~ 35 ms and midlatency responses ~ 40 – 60 ms in SI and long latency responses peaking at ~ 100 ms in SII (Forss, Salmelin, & Hari, 1994; Jousmäki, 2000; Jousmäki & Forss, 1998). Compared to electric stimulation of the median nerve, tactile stimulation of the fingers presented via air-puff, pneumatic, or piezoelectric stimulators elicits SI responses that are smaller in amplitude and longer in latency (Forss et al., 1994; Jousmäki, 2000). In addition to the stimulus type, the rise time of a tactile stimulator has to be considered when comparing latencies of somatosensory evoked responses. Cortical responses to tactile air-puff stimuli were observed to peak in SI at 30–60 ms and in bilateral SII at 90–100 ms (Forss et al., 1994; Huttunen, 1986). Jones, Pritchett, Stufflebeam, Hamalainen, and Moore (2007), who presented similar brief tactile stimuli with a piezo-electric stimulator, reported the most prominent SI

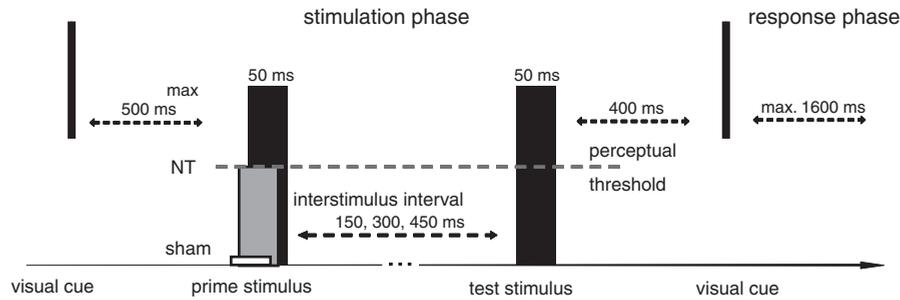


Figure 1. Scheme of stimulation sequences. Pairs of short tactile stimuli (50 ms) consisted of an intensity-varying stimulus (prime stimulus: clearly suprathreshold [max], near-threshold [NT], or sham [sham] stimulation) followed by a suprathreshold test stimulus. Stimulus pairs were presented with interstimulus intervals of 300 ms in Experiment 1 and 150, 300, or 450 ms in Experiment 2. The start and end of the stimulation phase were indicated by a visual cue (represented by vertical lines) 500 ms before the prime stimulus and 400 ms after the test stimulus, respectively. After each stimulation phase, participants were requested to indicate the number of stimuli perceived by pressing one of two buttons within a response phase of 1.6 s.

activation at ~ 70 ms and earlier responses at 25, 35, and 50 ms with smaller amplitudes and a low signal-to-noise ratio. In the present study, the tactile stimuli were short tactile pulses presented in the form of half a cycle of a sine wave of 50 ms duration, that is, maximum rod protrusion was reached after a delay of ~ 25 ms. Therefore, latencies of the evoked responses were expected to be longer than latencies reported for median nerve stimulation.

Somatosensory evoked neuromagnetic responses that were time-locked to the presentation of the test stimulus were averaged across trials and recording sessions for the four conditions (sham, BT, AT, and max). Each of these averages revealed field distributions typical for somatosensory evoked responses (Hari et al., 1984) showing two components, one in the latency range from 60 to 90 ms (peaking at ~ 70 ms) and the other from 90 to 120 ms (peaking at ~ 110 ms). The earlier SI responses reported by Jones et al. (2007) were very weak and inconsistent in the present data. Therefore, data analysis focused on the two most prominent peaks. Whereas the topography for the first peak displayed a clear SI activation contralateral to the stimulation site, the second peak revealed bilateral activation in secondary somatosensory cortex (SII). For source modeling of the different components of the evoked response, the means from all conditions were computed for each participant. For this reason, special care was taken to maintain the head position fixed with respect to the MEG sensors throughout the recordings by stabilizing the participant's head with cushions and a chin rest. Before and after each recording, the head position relative to the sensor positions was measured. Recordings with head movements greater than 5 mm were repeated. Participants were excluded from data analysis if the signal-to-noise ratio was below 1.5 or if their data did not show the typical field patterns described above.

To analyze the attenuation of test stimulus responses in somatosensory cortical areas, dipole models (DipoleFit 5.4; VSM MedTech Ltd., Port Coquitlam, Canada) representing the activated sources in SI and SII were fitted separately at single time points of the two components of the test stimulus response in the grand means of individual participants (Figure 2). For the first peak, one dipole (Dipole 1) modeled the SI activity contralateral to the stimulated finger. A second dipole was added to account for spurious activity if the first dipole did not explain at least 90% of the variance of the magnetic field. The second dipole was excluded from further analysis.

A two-dipole model (Dipole 2 contralateral and Dipole 3 ipsilateral to the stimulated finger) was used for the second peak

to model the bilateral activation of SII. Again, an additional dipole that was excluded from further analyses was used to model spurious brain activity if the dipole model did not explain 90% of the variance of the magnetic field. The orientation of Dipole 1, modeling the first peak, pointed mainly toward an anterior–posterior direction, whereas the orientation of Dipoles 2 and 3, modeling the bilateral activity of the second peak, pointed toward an inferior–superior direction. Assuming invariant source locations for all stimulation conditions, individual source activities were calculated for each of the four stimulation conditions using subspace projection (Scherg & Ebersole, 1993).

Based on the dipole locations, the temporal course of dipole amplitude in a time window ranging from 60 to 90 ms (Dipole 1) and 100 to 130 ms (Dipoles 2 and 3) with respect to stimulus onset was calculated for the different stimulation conditions using subspace projection. For statistical analyses, only the maximum peak amplitudes of dipole activity within these time windows were compared for the different stimulation conditions.

Repeated measure one-way analyses of variance (ANOVAs), with the within-factor Condition and four levels (sham, BT, AT and max), were applied to assess the statistical significance of the activity parameters of the three sources. Greenhouse–Geisser correction was applied to correct for violations of sphericity. In reporting significance levels, the uncorrected degrees of freedom are given along with the ϵ values used to adjust the degrees of freedom in determining the significance level. A significant main effect of Condition was the prerequisite for further post hoc pairwise comparisons of conditions, and a significance level of $p < .05$ was applied. To correct for Type I errors, the Bonferroni–Holm correction (Holm, 1979) was applied for multiple pairwise comparisons.

Results

Behavioral Results

Participants could easily discern the number of stimuli presented in control trials of the sham and max conditions with an overall mean accuracy of $>90\%$ (mean \pm standard error: max: $95.61 \pm 1.01\%$, sham: $92.64 \pm 2.29\%$). Due to the adaptive staircase method for the intensity of near-threshold stimuli, the proportion of BT and AT trials was roughly balanced (BT: $50.86 \pm 1.05\%$, AT: $49.14 \pm 1.05\%$). Intensities of near-threshold stimuli varied remarkably across participants as well as within experimental blocks (similar to the distribution in Experiment 2

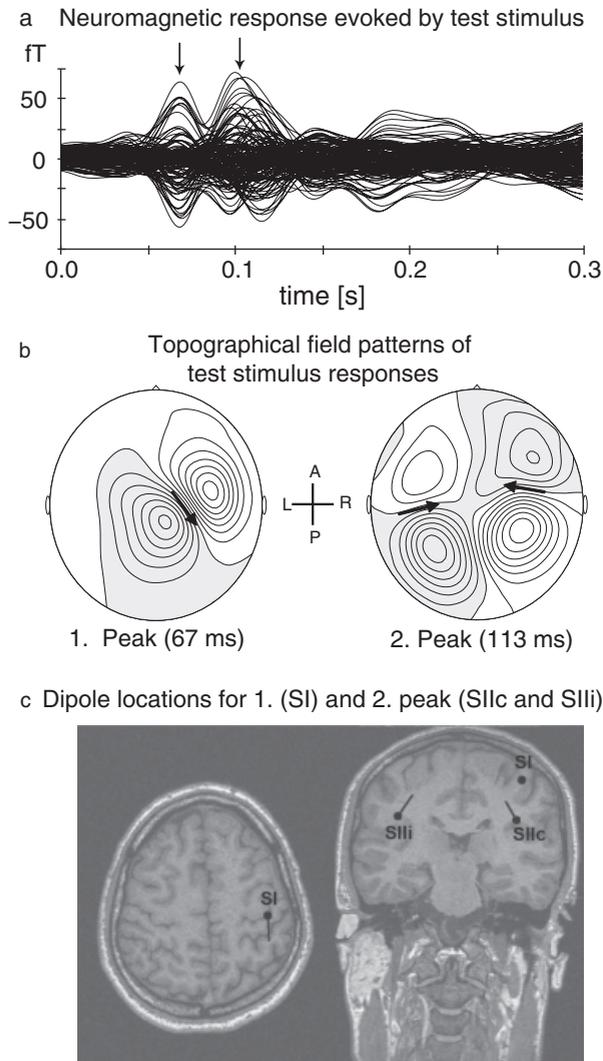


Figure 2. Source modeling of neuromagnetic responses evoked by the test stimuli. **a:** Neuromagnetic responses evoked by the test stimuli. The response shows two distinct activity peaks at 60–90 ms and 90–120 ms. **b:** Magnetic field patterns of the first and second peak, representing typical activation in primary (left pattern) and secondary somatosensory cortex (right pattern). **c:** Dipole locations. Mean source locations were based on the individual grand means of neuromagnetic activity. Sources were located in primary (SI) and bilateral secondary (SIIi: ipsilateral, SIIc: contralateral) somatosensory cortex. Results were superimposed onto an individual MRI.

as illustrated in Figure 4a, below) due to fluctuations of individual perceptual thresholds. The mean intensities of individual participants ranged from 9.07% to 31.14% (of maximum stimulus intensity). By virtue of the adaptive staircase method, stimulus intensity was systematically higher in AT trials than in BT trials. Nevertheless, intensities of AT and BT trials were clearly within same range (as illustrated in Figure 4b, below).

The *F* test, comparing the difference between the mean of stimulus intensities for AT and BT trials with the overall variance of intensities for each experimental block and individual participants revealed that the intensity difference between AT and BT trials was well within the range of random fluctuations of stimulus intensities due to the variation of the threshold across the experiment.

Somatosensory Evoked Responses

Differences in amplitudes of cortical responses as a result of stimulation condition were analyzed using the dipole models representing sources of stimulus-specific activation in SI and SII (Figure 2). These models were determined separately for the two prominent components at peak maxima for averaged responses evoked by the test stimulus with a mean latency of 72.9 ± 5.3 ms for SI responses (Dipole 1) and 113.3 ± 1.6 ms for bilateral SII responses (Dipoles 2 and 3). The calculated dipole activities peaked at similar latencies in contralateral (109.8 ± 8.1 ms) and ipsilateral SII (111.5 ± 10.4 ms) that did not differ significantly, $F(1,13) = 0.38, p = .548$.

In comparing the peak amplitudes of the different conditions, responses in bilateral SII revealed a significant effect for the within-factor Condition (Figure 3 and Table 1). Whereas the

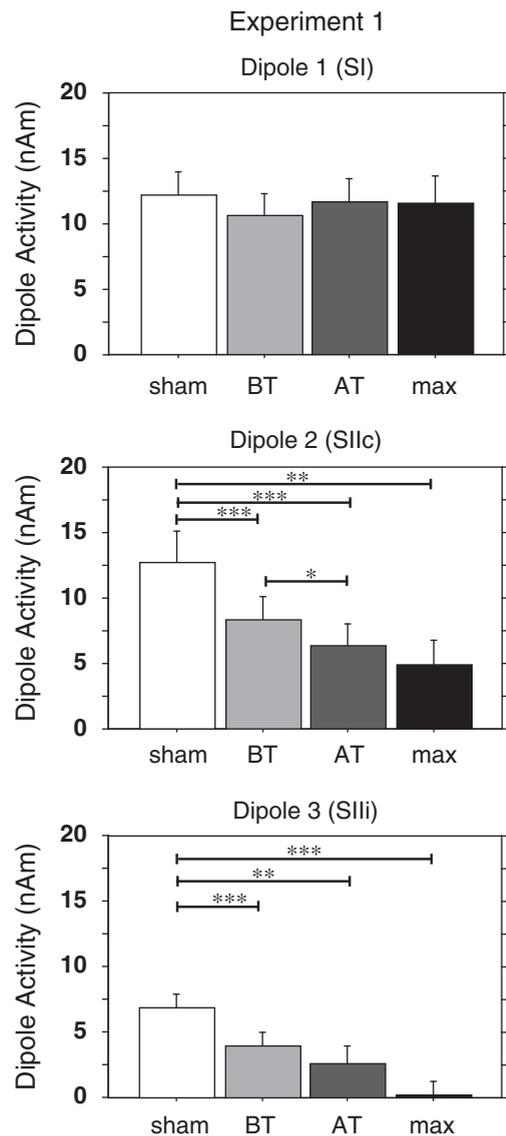


Figure 3. Dipole activity in Experiment 1. Mean peak amplitudes of dipole activity elicited by the test stimulus (Dipoles 2 and 3). Results are shown for the near-threshold conditions BT and AT (below and above the perceptual threshold) and the control conditions sham and max. Dipole 1 represents activation in SI and Dipoles 2 and 3 activations in bilateral SII (SIIc: contralateral, SIIi: ipsilateral). Significant differences between peak amplitudes are marked by *** ($p \leq .001$), ** ($p \leq .01$), and * ($p \leq .05$).

Table 1. Experiment 1: Statistical Analyses for Peak Amplitudes of Dipole Activity Evoked by Test Stimuli

	Dipole 1 (SI)		Dipole 2 (SIIc)		Dipole 3 (SIII)			
	<i>F</i>	<i>p</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>p</i>		
Condition	$F(3,39) = 0.90$; $\epsilon = .697$	.421	Condition	$F(3,39) = 12.59$; $\epsilon = .479$	<.0001	Condition	$F(3,39) = 14.32$; $\epsilon = .546$	<.0001
sham-max			sham-max	$F(1,13) = 14.58$	.0021	sham-max	$F(1,13) = 28.65$	.0001
sham-AT			sham-AT	$F(1,13) = 25.77$	.0002	sham-AT	$F(1,13) = 12.23$	.0029
sham-BT			sham-BT	$F(1,13) = 32.72$	<.0001	sham-BT	$F(1,13) = 70.73$	<.0001
AT-BT			AT-BT	$F(1,13) = 6.03$	.029	AT-BT	$F(1,13) = 1.60$	.2285

Peak amplitudes of dipole activity were analyzed with a one-way ANOVA including the factor Condition and the levels AT, BT, sham, and max, for Dipole 1 (SI) and Dipoles 2 (SIIc) and 3 (SIII). The significance of the main effect is shown. In the case of a significant main effect Condition, post hoc analyses results are presented.

comparison of amplitudes across conditions revealed a systematic pattern of amplitude reduction for bilateral SII, amplitudes in SI did not significantly differ across conditions.

Responses in SII showed significant reduction of peak amplitudes in both hemispheres for the BT, AT, and max conditions in comparison to the sham condition. This effect was strongest

for the control condition max, involving a clearly suprathreshold prime stimulus, and intermediate for the near-threshold conditions BT and AT. In SIIc, the clearly suprathreshold stimulus in the max condition attenuated the test stimulus responses to or even below baseline level, resulting in negative dipole activities. Note that the negative dipole moment did not deviate significantly from zero. Perception of the near-threshold stimulus significantly increased the extent of amplitude reduction between the conditions AT and BT in the contralateral SII (SIIc) but not in the ipsilateral SII (SIIi).

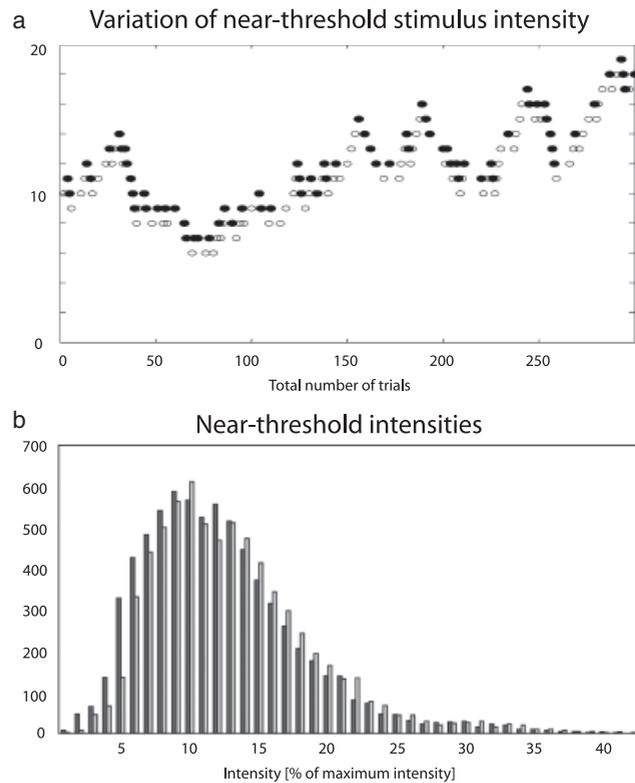


Figure 4. Distribution of near-threshold intensities. a: Variation of perceptual thresholds during an experimental block. The intensity for near-threshold stimulation was constantly adapted to the individual perceptual threshold. The diagram shows the variation of near-threshold intensities for a single participant during a single experimental block of 300 trials. The intensities of trials for the control conditions (sham and max) are not shown in the diagram. Trials with below-threshold stimulation are depicted by open circles and trials with above threshold stimulation by closed circles. b: Distribution of above- and below-threshold intensities. The distributions of near-threshold intensities show a large overlap of above-threshold (light gray bars) and below-threshold (dark gray bars) trials, indicating that above- and below-threshold trials are within the same intensity range, and differences in cortical processing of near-threshold trials are due to conscious perception rather than a result of intensity differences.

Discussion

These results clearly demonstrate that tactile stimuli affect the cortical processing of a subsequent stimulus when presented in pairs with an ISI of 300 ms. The cortical responses of test stimuli in SII were reduced in amplitude as a function of intensity and perception of the preceding stimulus. Along with the weak cortical activation, the presentation of near-threshold stimuli also resulted in a reduction of dipole source amplitudes obtained for subsequent test stimuli. For the ISI of 300 ms, the cortical responses in SI to test stimuli were not affected by preceding near-threshold stimuli. On the basis of previous studies (Forss, Jousmäki, & Hari, 1995; Maugiere et al., 1997; Mertens & Lütkenhöner, 2000; Wikström et al., 1996; Zhu, Disbrow, Zumer, McGonigle, & Nagarajan, 2007) reporting reduced SI responses for trains of stimuli using ISIs of up to ~ 1 s, we hypothesized that SI responses to the test stimulus would also be reduced by the preceding prime stimulus. Given that neither near-threshold stimuli nor the maximum intensity stimuli affected the SI responses to the test stimuli, it seems rather unlikely that the near-threshold stimulus intensity was too low to produce effects in SI. More likely is that the ISI of 300 ms is too long to reduce the SI response to the second stimulus within the stimulus pairs. Either shorter ISIs or longer trains of stimuli seem to be necessary to obtain amplitude reductions for SI responses.

EXPERIMENT 2

In the second experiment, the paired-stimulus paradigm was applied with three different ISIs (150, 300, and 450 ms). Using ISIs of different length, we wanted to study whether the time lag between the prime and the test stimulus affects the extent of amplitude reduction. ISI-dependent amplitude reductions might provide insight into the temporal dynamics of the processing of near- and suprathreshold stimuli. In reducing the ISI to 150 ms, it was of particular interest whether SI activity could be modulated.

Another goal of the second experiment was to determine the most suitable ISIs for the paired-stimulus paradigm, namely, that which results in the largest effects of amplitude reduction between conditions. For either of the ISI, we expected similar effects in SII responses and additional amplitude reductions in SI for the shortest ISI. We hypothesized that, for the shortest ISI of 150 ms during the presentation of the test stimulus, the neuronal assembly preactivated by the prime stimulus would not be fully recovered yet, resulting in amplitude reductions of SI responses. Furthermore, we hypothesized that the extent of amplitude reduction would decrease with increasing ISIs. Therefore, stimulus pairs were also presented with the longest ISI of 450 ms.

Methods

Participants

Twelve healthy right-handed participants (8 women and 4 men, mean age \pm standard deviation: 22.83 ± 1.70 years, range 21–25 years; none of them had been enrolled in Experiment 1) participated in Experiment 2. In the course of data analysis, one of the participants was excluded from the analysis of neuromagnetic responses due to a low signal-to-noise ratio, rendering source localization impossible.

Stimulation

The same paradigm and experimental setup as in Experiment 1 was used for Experiment 2. Stimulus pairs were presented with ISIs of 150, 300, and 450 ms. The increased number of conditions (sham, max, and NT, with NT subdivided into BT and AT, for each of the ISIs) necessitated a higher number of total trials and thus required longer recording sessions. For this reason, the experiment was conducted on two consecutive days with four recording sessions each. Efforts were made to ensure that the head position was the same on both days. During the continuous MEG recordings lasting 720 s each, 300 trials were presented with nine different conditions in random order (NT trials were presented twice as often as trials of the control conditions, sham and max) resulting in a total number of 200 trials per condition after the subcategorization of NT trials. The same method of source analysis and estimation of dipole activity as in Experiment 1 was used. Again, components of evoked magnetic fields were modeled by three dipoles. Peaks of dipole source activities for different stimulation conditions were determined. Two-way ANOVAs with the within-factors Condition (levels: sham, BT, AT, and max) and ISI (levels: 150, 300, and 450) were applied to the activity parameters of the three sources. A significant main effect of Condition was the prerequisite for further post hoc pairwise comparisons of conditions. For the multiple pairwise comparisons, the Bonferroni–Holm correction (Holm, 1979) was applied.

Results

Behavioral Results

As in Experiment 1, the percentage of correct responses in the control conditions, sham and max, was well above 90% (mean \pm standard error: max: $97.94 \pm 0.49\%$, sham: $94.01 \pm 0.89\%$), indicating that participants were paying attention to the task and responding vigilantly. Therefore, the proportion of NT conditions AT and BT was roughly balanced, with percentages of $51.15 \pm 1.13\%$ in the BT condition and $48.85 \pm 1.13\%$ in the AT condition.

Intensities of near-threshold stimuli varied remarkably across participants as well as within experimental blocks (Figure 4a) because of fluctuations of individual perceptual thresholds. The mean intensities of individual participants ranged from 5.77% to 17.57% (of maximum stimulus intensity). With respect to the different stimulation conditions, the variation of ISIs did not affect mean threshold intensity (ISI150: $12.66 \pm 5.1\%$, ISI300: $12.64 \pm 4.99\%$, ISI450: $12.70 \pm 5.04\%$), $F(2,22) = 0.55$, $p = .533$, $\epsilon = .727$. Because of the applied staircase method, the intensity of AT stimuli was slightly higher than for BT stimuli. However, the difference of intensities between both near-threshold conditions was well within the range of the intensity fluctuations across trials, as indicated by the F test.

Somatosensory Evoked Responses

The neuromagnetic responses to test stimuli in the different stimulation conditions were analyzed in the same way as in Experiment 1. Dipole models representing stimulus-specific sources in somatosensory cortices were fitted separately for SI (Dipole 1: 71.2 ± 3.9 ms) and bilateral SII (Dipoles 2 and 3: 110.03 ± 7.4 ms). The latencies of peaks in contralateral (111.4 ± 6.9 ms) and ipsilateral (114.4 ± 9.89 ms) SII did not differ significantly, $F(1,10) = 3.080$, $p = .110$.

The statistical analyses for the three dipoles including all conditions and ISIs displayed comparable effects on peak amplitudes across conditions as in Experiment 1 (Figure 5 and Table 2). Responses in SI were not significantly affected by preceding stimulation. Neither the main factors Condition and ISI nor the interaction of these factors revealed significant differences between stimulation conditions. Stimulus processing in bilateral SII revealed significant effects due to previous stimulation with different ranges of amplitude reduction across conditions. The two-way ANOVAs revealed a significant main effect for the factor Condition, but there were no significant effects for the factor ISI nor for the interaction Condition \times ISI. Based on the significant main effect Condition, initial post hoc tests, comparing pairs of conditions, were calculated to determine the general difference between the peak amplitudes of the different stimulation conditions within all ISIs.

For SIIc as well as SIII, post hoc tests comparing pairs of conditions revealed significant effects with different ranges of amplitude reduction as a result of the intensity and the perception of the preceding prime stimuli. The effect of peak amplitude reduction was strongest for the max condition and intermediate for near-threshold stimuli. In SIII, the clearly suprathreshold stimulus in the max condition attenuated the test stimulus responses to or even below baseline level, resulting in negative mean of dipole activities. Note that the negative dipole moment did not deviate significantly from zero. Amplitude reductions were significantly smaller for perceived above-threshold stimuli than for missed below-threshold stimuli.

Discussion

The cortical responses to test stimuli were similarly affected by the preceding stimulation for either of the ISIs. The nonconscious processing of near-threshold stimuli in BT trials resulted in reduced SII responses to the test stimuli. The conscious perception of the near-threshold stimuli in the AT condition, as well as the stronger intensity of the prime stimuli in the max condition, increased the extent of amplitude reduction in SII. This indirect measure for cortical activation indicates that the direct SII re-

sponse to tactile stimuli is modulated by stimulus intensity as well as by the conscious perception of the stimulus.

Although the two-way ANOVA did not reveal significantly different patterns of amplitude reductions for the three ISIs, the bar plots of peak amplitudes (Figure 5) indicate that the effect of amplitude reduction due to near-threshold stimuli that are consciously perceived (AT trials) tends to decrease with increasing ISIs. This trend might be of importance for the determination of the ISI most suitable for the paired-stimulus paradigm as well as for further investigations of the temporal aspects of amplitude reductions with a larger number of participants or over a wider range of ISIs. This trend is noteworthy, because the one-way ANOVAs (Figure 5 and Table 3) with the main factor Condition that were calculated for the individual ISIs revealed that the extent of amplitude reduction due to the perception of near-threshold stimuli (AT condition) varied significantly across ISIs, $F(2,20) = 5.042, p = .036, \epsilon = .640$.

For the shorter ISIs of 150 and 300 ms, perception of near-threshold stimuli (AT condition) resulted in significantly lower peak amplitudes than in trials with missed near-threshold stimuli (BT condition). For the longest ISI of 450 ms, peak amplitudes of the BT and AT conditions no longer revealed a significant difference. This difference in trend suggests that ISIs of < 450 ms might be more suitable for the application of a paired-stimulus paradigm to study the neuronal correlates of conscious perception in the somatosensory system. Although these findings need to be corroborated and verified by further studies, this trend indicates that a wider range of ISIs or a larger number of participants could reveal significant differences in amplitude reductions across ISIs for consciously perceived near-threshold stimuli.

Although the shortest ISI of 150 ms was well within the range of ISIs that were reported to reduce SI responses within stimulus trains, SI responses were not systematically affected by the preceding stimulation (Wikström et al., 1996).

General Discussion

In the present neuromagnetic study, we tested the applicability of a paired-stimulus paradigm for the investigation of near-threshold stimulus processing in somatosensory cortical areas by means of differences in response amplitude due to conscious perception. Because of the low activations for the direct response in anticipation of near-threshold stimulation as shown by Torquati et al. (2002), we investigated the effect of near-threshold stimuli on the cortical processing of a succeeding test stimulus. With the combination of this indirect approach and the high temporal resolution of magnetoencephalography, we expected to determine the magnitude and duration of cortical activation to near-threshold stimuli and possibly the differences in activation due to perception of the stimuli. Cortical responses to the clearly suprathreshold test stimuli were significantly reduced as a function of perception and intensity of the preceding prime stimuli. Yet, this effect was limited to bilateral SII. Using ISIs of 150, 300, and 450 ms, SI responses were not affected by preceding stimuli.

Despite the lack of a significant interaction for the main factors Condition and ISI, which implied that patterns of amplitude reductions did not differ significantly for the three ISIs, there seems to be a noteworthy tendency, as it might be a starting point for further examinations. A possible index of the importance of the different ISIs on the reduction of the dipole activity might be the post hoc analyses for individual ISIs. The post hoc analyses

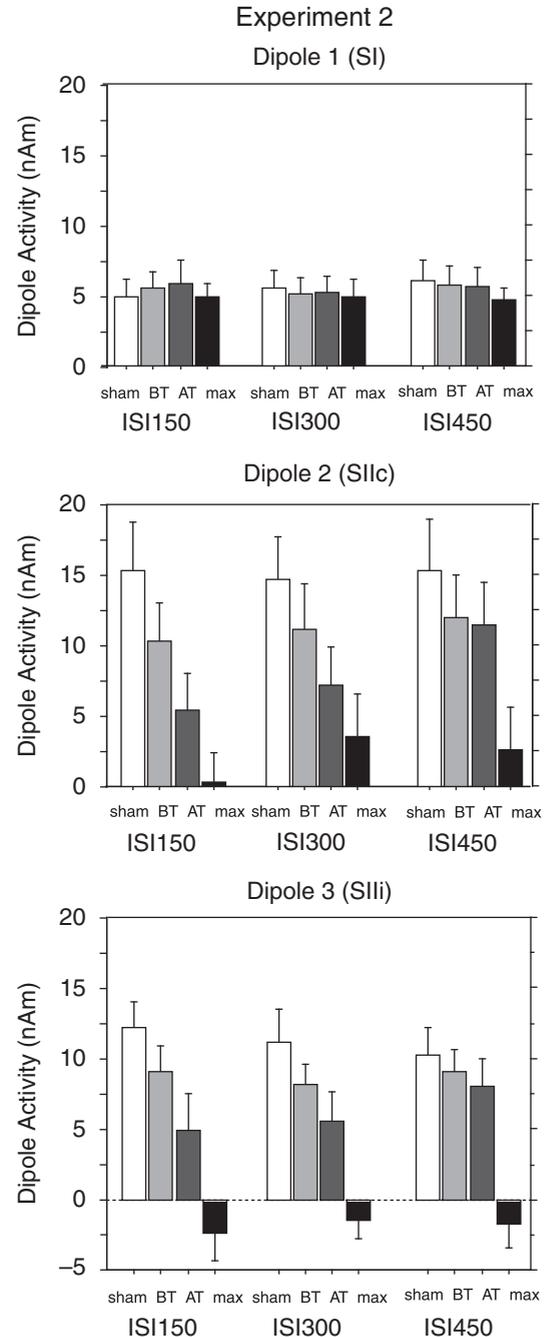


Figure 5. Dipole activity Experiment 2: Mean peak amplitudes of dipole activity elicited by the test stimulus (Dipoles 2 and 3). Results are shown for the near-threshold conditions BT and AT (below and above the perceptual threshold) and control conditions sham and max separately for each of the interstimulus intervals (ISI150, ISI300, and ISI450).

suggested that the magnitude of response reduction in SII tended to decrease with increasing ISIs for near-threshold prime stimuli that were consciously perceived. Hence, differences in the SII responses due to the perception of the preceding near-threshold stimuli might only last up to an ISI of 300 ms.

Effect of Near-Threshold Stimuli on the Cortical Processing of Succeeding Stimuli

Based on the present results, the paired-stimulus paradigm seems to be a promising approach for neurophysiological studies in that

Table 2. Experiment 2: Statistical Analyses for Peak Amplitudes of Dipole Activity Evoked by Test Stimuli

	Dipole 1 (SI)		Dipole 2 (SIIc)		Dipole 3 (SIII)			
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>		
Condition	$F(3,30) = 0.84$; $\epsilon = .434$	.484	Condition	$F(3,30) = 29.92$; $\epsilon = .579$	<.0001	Condition	$F(3,30) = 27.37$; $\epsilon = .560$	<.0001
ISI	$F(2,20) = 0.51$; $\epsilon = 0.980$	.603	ISI	$F(2,20) = 3.81$; $\epsilon = .570$	.072	ISI	$F(2,20) = 0.15$; $\epsilon = .673$	.776
Condition × ISI	$F(6,60) = 0.48$; $\epsilon = .458$	.686	Condition × ISI	$F(6,60) = 1.93$; $\epsilon = .478$	.149	Condition × ISI	$F(6,60) = 0.92$; $\epsilon = 0.644$	.458
			sham-max	$F(1,10) = 41.53$	<.0001	sham-max	$F(1,10) = 33.86$	.0002
			sham-AT	$F(1,10) = 19.27$	.0014	sham-AT	$F(1,10) = 12.75$	.0051
			sham-BT	$F(1,10) = 17.51$	.0019	sham-BT	$F(1,10) = 7.08$	.0238
			BT-AT	$F(1,10) = 16.23$	.0024	BT-AT	$F(1,10) = 5.29$	.0443

Peak amplitudes of dipole activity were analyzed with a two-way ANOVA including the factors Condition and ISI and the levels, AT, BT, sham, and max for Dipole 1 (SI) and Dipoles 2 (SIIc: secondary somatosensory cortex contralateral to the stimulated finger) and 3 (SIII: secondary somatosensory cortex ipsilateral to the stimulated finger). The significance of the main effects are shown. In the case of a significant main effect Condition, post hoc analyses results are presented.

it allows the investigation of different aspects of near-threshold stimulus processing such as amplitude, duration, and the spatial extent of activation. In the present study, intensity as well as conscious perception of the prime stimulus resulted in decrements of the cortical responses to the subsequent test stimulus.

Decrements in amplitudes of evoked brain responses due to preceding stimulation within pairs and trains of above-threshold stimuli have previously been demonstrated in various MEG studies (Ahlfors, Ilmoniemi, & Prtin, 1993; Angel, Quick, Boylls, Weinrich, & Rodnitzky, 1985; Forss et al., 1995; Maugiere et al., 1997; Nagamine et al., 1998; Tiihonen, Hari, & Hämäläinen, 1989; Wikström et al., 1996). The extent of response decrement to above-threshold stimuli is markedly influenced by the ISI between the successive stimuli, and it differs for different components of the evoked magnetic fields peaking at different latencies. The attenuation profile of somatosensory responses has previously been regarded as an indicator of the lifetime of sensory memory in somatosensory areas, which relates to the functional aspects of evoked responses (Hamada et al., 2002). Because of this, information processing within a cortical area is not only indicated by activation in the respective brain area but also by the ability to interfere with a subsequent stimulus. Thus, we expected reduced response amplitudes for the test stimulus—even for the very weak neuronal preactivation by near-threshold stimuli.

Despite variation of the ISI in the present study, no definite conclusion about ISI-dependent response decrements following near-threshold somatosensory stimuli can be drawn. Although no significant effect of ISIs was found in the overall analysis,

differential effects for the analyses of individual ISIs suggest that variation of the ISI might modulate the extent of the response decrements for near-threshold stimuli. Similar to our paradigm, Blankenburg et al. (2003) used a paired-stimulus paradigm in an functional magnetic resonance imaging (fMRI) experiment to investigate the impact of subliminal stimuli on the cortical processing of succeeding suprathreshold stimuli. In their study, subliminal stimuli preceding clearly detectable stimuli with a short ISI of 30 ms significantly reduced the BOLD response evoked by succeeding stimuli predominantly in SI as well as SII and supplementary motor area (SMA).

In contrast to Blankenburg et al. (2003), who studied the compound neuronal activity of the stimulus pair because individual responses to prime and test stimuli cannot be disentangled in fMRI due to the long time constant of the BOLD response, we presented stimulus pairs with ISIs ≥ 150 ms that enabled us to study cortical responses to the individual stimuli without any overlap of cortical activations (Ahlfors et al., 1993).

Unlike the results from Blankenburg et al. (2003), the effects in our study were limited to bilateral SII. Cortical responses in SII that peaked at ~ 110 ms were significantly affected by previous stimulation. The magnitude of response reduction strongly depended on the intensity and the perception of the prime stimulus. The response reduction due to preceding stimuli clearly outlasted the longest ISI of 450 ms, with stronger effects in the max condition than in the NT conditions. Whereas in Blankenburg et al. (2003) reduced BOLD responses due to previous subliminal stimulation occurred predominantly in SI, magnetic

Table 3. Experiment 2: Statistical Post Hoc Analyses for Peak Amplitudes of Dipole Activity Evoked by Test Stimuli in SIIc (Dipole 2)

	ISI150		ISI300		ISI450			
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>		
All conditions	$F(3,30) = 18.56$; $\epsilon = .671$	<.0001	all conditions	$F(3,30) = 16.22$; $\epsilon = .707$	<.0001	all conditions	$F(3,30) = 17.77$; $\epsilon = .511$	<.0001
Sham-max	$F(1,10) = 51.79$	<.0001	sham-max	$F(1,10) = 26.52$	.0004	sham-max	$F(1,10) = 24.06$	.0006
Sham-AT	$F(1,10) = 11.85$	.0063	sham-AT	$F(1,10) = 18.00$	.0017	sham-AT	$F(1,10) = 12.24$	.0057
Sham-BT	$F(1,10) = 5.79$	.037	sham-BT	$F(1,10) = 12.29$	.0057	sham-BT	$F(1,10) = 11.50$	.0069
BT-AT	$F(1,10) = 12.16$	.0059	BT-AT	$F(1,10) = 10.49$	.0089	BT-AT	$F(1,10) = 0.27$	.6172

Amplitude reductions of dipole activity in contralateral secondary somatosensory cortex (SIIc) across conditions were further analyzed in post hoc analyses. The one-way ANOVAs with the factor Condition and the levels, AT, BT, sham, and max that were calculated for individual ISIs indicate that the effect of amplitude reduction tends to decrease with increasing ISI for near-threshold stimuli above the perceptual threshold (AT condition).

brain responses in SI evoked by test stimuli were not affected by previous stimulation in our study using ISIs of 150, 300, and 450 ms between the stimuli.

Studies investigating the temporal integration (Forss et al., 1995; Mugiore et al., 1997; Mertens & Lütkenhöner, 2000; Nagamine et al., 1998; Tiihonen et al., 1989; Wikström et al., 1996; Zhu et al., 2007) and the recovery cycle of somatosensory evoked responses (Hamada et al., 2002; Hari et al., 1993) have shown that the temporal dynamics of cortical responses differ enormously for SI and SII. The decrease of response amplitude resulting from repeated stimulus presentation was smaller and the recovery cycle was shorter in SI than in SII. In most studies, early somatosensory responses originating in SI were only suppressed when stimuli were presented with ISIs below 150 ms. In contrast to our results, SI responses later than 30 ms are also decreased by repetitive presentation of electrical (Forss et al., 1995; Mugiore et al., 1997; Wikström et al., 1996) and mechanical stimuli (Mertens & Lütkenhöner, 2000; Zhu et al., 2007) with longer ISIs that correspond to the ISIs chosen for the present experiments. All of these studies presented stimulus trains of more than 100 stimuli. Hamada et al. (2002) reported that in trains of stimuli, responses to the second stimulus were smaller than those to the first stimulus, but significant attenuations were only observed from the third stimulus on. The suppression by a single stimulus preceding the test stimulus, as in the stimulus pairs presented in our study, might not be sufficient and enduring enough to evoke a response decrement in SI. Therefore, the ISIs of at least 150 ms in our study might have been too long to produce measurable effects for the stimulus pairs in SI. Because sensory information is mainly passed from SI to SII after a short delay, interactions within SI for subsequently applied stimuli can only be observed for ISIs shorter than the lifetime of sensory memory in SI. In the case of an ISI exceeding the activation and recovery period, the original response of the second stimulus is reestablished. According to this logic, and to the findings from evoked response studies, stimulus information is processed very briefly in SI.

Difference in Cortical Processing due to Conscious and Subconscious Stimulus Perception

Near-threshold somatosensory stimuli have mainly been used to investigate the cortical mechanisms associated with conscious perception in the somatosensory system (Braun, Hess, Burkhardt, Wühle, & Preissl, 2005; de Lafuente & Romo, 2005; Jones et al., 2007; Libet, Alberts, Wright, & Feinstein, 1967; Meador, Ray, Day, Ghelani, & Loring, 1998; Meador, Ray, Day, & Loring, 2001; Meador, Ray, Echaz, Loring, & Vachtsevanos, 2002; Palva, Linkenkaer-Hansen, Naatanen, & Palva, 2005; Ray et al., 1999; Schweizer et al., 2000, 2001). Several experimental paradigms have been applied using various techniques such as psychophysical experiments (Braun et al., 2005; Schweizer et al., 2000, 2001), subdural recordings (Libet et al., 1967; Meador et al., 2002; Ray et al., 1999), and noninvasive brain imaging techniques like fMRI (Blankenburg et al., 2003) and magnetoencephalography (Jones et al., 2007; Palva et al., 2005) to investigate differences in brain responses due to conscious perception. It has been shown that the processing of consciously perceived above-threshold and missed below-threshold somatosensory stimuli involves a widespread network, including the SI and SII and higher cortical areas (Blankenburg et al., 2003; Libet et al., 1967; Meador et al., 2002; Ray et al., 1999).

The results in the present study replicated the previous findings that neuronal correlates of conscious perception—namely, differences in cortical responses between near-threshold stimuli

that are consciously perceived and those that are missed—can already be found in somatosensory cortices. In our study, differences in cortical responses due to conscious and subconscious perception were only seen in SII. The magnitude of amplitude reduction for the test stimulus response was bigger for perceived than for missed near-threshold stimuli.

Stronger amplitude reduction in SII for consciously perceived than for subconsciously processed stimuli might be explained by assuming that conscious perception activates additional neurons in this area and thus increases the effect of amplitude reduction of the succeeding stimuli. However, the duration of the effect was similar for perceived and missed near-threshold stimuli.

Most studies investigating the neuronal correlates of conscious perception in somatosensory cortical areas (de Lafuente & Romo, 2005; Libet et al., 1967; Meador et al., 1998, 2001, 2002; Ray et al., 1999; Schubert, Blankenburg, Lemm, Villringer, & Curio, 2006) found similar early evoked potentials for perceived and missed near-threshold stimuli in SI. Differences in cortical processing due to conscious perception occurred at later stages of the processing pathway involving SII and parietal and frontal cortical areas. Contradictory results were reported by Palva et al. (2005) and Jones et al. (2007), who found differences due to conscious perception already in the early responses of SI.

Despite the number of studies applying somatosensory near-threshold stimuli for the investigation of neuronal correlates of conscious perception, the role of somatosensory cortices, and especially that of SI, in conscious perception is still debated. The controversial results indicate that the involvement of somatosensory cortical areas in conscious perception is not yet fully understood. Discrepancies between findings related to the involvement of cortical areas in conscious perception might result from the low amplitudes of brain responses that are evoked by somatosensory near-threshold stimuli (Jousmäki & Forss, 1998; Torquati et al., 2002). Because of the weak neuronal responses, the investigation of cortical processing following near-threshold tactile stimulation requires more elaborate experimental designs than the analysis of brain responses to single near-threshold stimuli (direct approach).

The short-lasting effect in SI that did not outlast the ISIs that were used in the present experiments is the likely reason that the involvement of SI in conscious perception could not be evaluated. However, the role of SI in conscious perception could be subject to further studies using the paired-stimulus paradigm.

In studying the perception of near-threshold stimuli, it has to be considered that participants' performance in stimulus detection might vary across the experiment due to changes in vigilance and according to training by repetitive trial presentations. Thus, if the individual perceptual threshold is determined before the recording, it cannot be excluded that stimulus intensities are near the sensory threshold at the beginning of the experiment but exceed or fall below perceptual threshold during the session. Hence, by adapting the stimulus intensity with an adaptive staircase procedure based on the participant's response, we could ensure that stimulus intensity remained near the perceptual threshold for the entire experiment.

For the investigation of near-threshold stimulus processing using the paired-stimulus paradigm, additional factors besides the adaptation to near-threshold intensities have to be considered. First, when one studies conscious perception of tactile stimuli, it might be argued that during near-threshold stimulation participants were only arbitrarily responding from trial to trial, and therefore differences between neuronal correlates of above- and below-threshold stimuli are not related to conscious percep-

tion. However, in the present experiment, the high percentages of correct responses in control conditions (sham and max) showed that participants were compliantly responding, rendering it very unlikely that the assignment of trials was only random. Second, when one uses an adaptive procedure for the determination of stimulus intensities, it might be argued that intensities of below-threshold stimuli are significantly lower than intensities of above-threshold stimuli. In this case, conscious perception would be confounded by stimulus intensity. Because, as demonstrated in the present study, above- and below-threshold stimuli were within the same range of intensities, differences in cortical responses are, rather, due to different modes of stimulus perception than to stimulus intensities.

Conclusion

In conclusion, even though cortical responses in somatosensory areas evoked by near-threshold tactile stimuli are very weak, by

using the paired-stimulus paradigm presented in the present experiment, we could show that differences in cortical processing of tactile stimuli are caused by a combination of stimulus intensity and conscious stimulus perception. Stimulus information of below-threshold stimuli, even though they are not consciously perceived, is nonetheless processed in somatosensory cortical areas and affects the cortical processing of subsequent stimuli for ISIs of at least 450 ms. Neuronal correlates of conscious perception—namely differential effects of perceived above and missed below near-threshold stimuli on the processing of succeeding stimuli—could be found in SII. For further investigations, the paired-stimulus paradigm could be a useful tool to study different aspects of near-threshold stimulus processing. The post hoc analyses in Experiment 2 suggest that, for the investigation of neuronal correlates of conscious perception, ISIs < 450 ms, and for studying the temporal aspects of the interference effect, a wider range of ISIs would be necessary.

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(RECEIVED September 11, 2008; ACCEPTED July 8, 2009)