Activation of SI is modulated by attention: a random effects fMRI study using mechanical stimuli

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Animal experiments on tactile attention suggest a modulation of sensory processing on the level of sensory representations but correspondent neuroimaging data in humans is inconclusive. The present experiment used mechanical stimuli to study tactile processing while varying the focus of attention. Activations were contrasted between attend and ignore conditions, both of which employed identical stimulation characteristics and an active task. Random effects analysis revealed significant attention effects in area SI (primary somatosensory cortex) in that the blood oxygenation level-dependent response was greater for attended than for ignored stimuli. Modulations were further found in the secondary somatosensory cortex and the middle temporal gyrus. These findings suggest that stimulus processing at the level of primary representations in area SI is modulated by attention. *NeuroReport* 18:607–611 © 2007 Lippincott Williams & Wilkins.

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Introduction

The neuronal effects of tactile stimulus processing and attention have been addressed with various methods, including single-unit recordings in monkeys [1,2], somatosensory evoked potentials/fields [3,4–7], positron emission tomography [8–10] and functional magnetic resonance imaging (fMRI) [11–14]. These studies support the assumption that attention changes the response behaviour of neural populations. An unresolved question, however, is to what extent such attention-related modulations affect neurons in the primary somatosensory cortex SI. Some experiments suggest that the blood oxygenation level-dependent (BOLD) response (BOLD contrast) in SI increases with attention (e.g. [8,11]), whereas others failed to find significant SI activation differences between attended and unattended conditions [4–6,12]. An equally inconclusive picture emerges for the SI-generated P50 component of the somatosensory evoked potential or field, which shows attentive modulation in some studies [5,15] but not in others [16,17].

Attention effects are typically measured by contrasting stimulus-related activations in which attention is varied, and represent a relative measure. For example, single cell-recordings show that 16% of SI neurons increase their firing rates during a tactile discrimination task when compared with a passive ignore condition [1]. The number of attention-sensitive SI neurons rises to about 50% of tested neurons if the data is compared with an active ignore condition in which the attentional focus is guided away from the tactile events [18]. Such 'task effects' have also been noted in human neuroimaging experiments. Using positron emission tomography, Meyer *et al.* [8] measured attention effects in comparison with a passive and an active ignore condition, and found that the attend/active ignore comparison showed a significant increase in SI activation, whereas the attend/passive ignore comparison did not reveal any SI effects.

Using fMRI, Nelson and co-workers [14] found a significant increase in %-signal change and activation volume in SI with attention whereas Hämäläinen *et al.* [19] did not detect attention effects in SI. These opposing results may be explained by the different characteristics of the tasks employed in these experiments. In the Nelson study, the attend condition comprised detecting slight variations in the strength (stimulus amplitude) of the tactile stimuli; the ignore condition was passive and comprised a train of similar tactile stimuli. Thus, the two conditions varied not only with regard to attention, but also with the physical characteristics of the stimuli. It is therefore possible that the passive ignore condition introduced greater habituation effects than the attend condition, which may have inflated the activation differences between the two conditions. Hämäläinen's experiment, on the other hand [19], used an oddball paradigm in the ignore and the attend condition but the ignore condition was passive, that is participants were asked to ignore the tactile stimuli but no further task was given. Johansen-Berg and Lloyd [20] argue that controlling the attentional focus in the ignore condition is difficult when no distractor task is used to ensure the disengagement from the tactile stimuli. An alternative explanation for the lack of SI attention effects in Hämäläinen's study [19] may therefore lie in the passive nature of the ignore condition.

In the light of these considerations, the present experiment revisited the question of attentional modulation in area SI by combining the oddball paradigm with an active ignore condition so that we could vary the focus of attention whilst keeping the stimulus characteristics constant. In the attend condition, tactile events were task relevant and participants were asked to count rare target events. In the ignore condition, tactile events were irrelevant and the attentional focus was actively guided away from the tactile modality. Areas susceptible to attentional modulation were identified through second-level random effect analysis of the interaction contrast (attend–ignore).

Methods

Twenty right-handed volunteers (eight men) participated in the study (mean age=28.15 years, range=18–56). The study protocol was approved by the local ethics committee.

Stimuli were presented with a nonmagnetic, digitally controlled device (CATUS-compressed air tactile universal system, MARIARC, The University of Liverpool, Liverpool, UK), which drives a piston through compressed air in a frequency range of 0.2–2 Hz. A circular 8 mm foam top was attached to the piston, so that each piston cycle caused a gentle indentation of the glabrous skin, providing a naturalistic activation of the mechanoreceptors. The stimuli were delivered to the tip of the right middle finger, D3. To reduce hand movements, all fingers other than D3 were secured with plastic tubing on a vertical support board. To control for potential cross-modal effects, participants were blindfolded during the scanning.

The task was based on the oddball paradigm and consisted of two types of stimuli, frequent standards and rare deviants. The standard stimuli were created with a piston cycle of 0.813 Hz, which produced a regular train of single prodding events. The deviant stimuli consisted of two consecutive 0.4 Hz piston cycles that were perceived as double prods interspersed in the train of single prod events. In each 15 s on-period, the train of standard stimuli was interspersed with 0–3 deviants (deviant likelihood 0–16.7%). Before the scanning, participants were familiarized with the two types of stimuli and practised the discrimination.

The experiment consisted of two tasks. In the active touch condition ('attend'), the tactile stimuli were task-relevant and participants were asked to focus their attention on the tactile events by silently counting the deviants (targets). Thereby, no information was given about the maximal/minimal number of target events. In the passive touch condition ('ignore'), the tactile stimulus protocol was identical except that, this time, participants were asked to ignore the tactile events and perform a mental arithmetic task (backward subtraction). The latter was chosen as a measure to actively disengage attention from the tactile events. After each block, participants were asked to give either their target counts (attend condition) or the result of their mental calculation (ignore condition) verbally.

Imaging data was collected with a 1.5-T GE MRI system. The BOLD contrast was obtained from T2*-weighted echo planar imaging (EPI) (TR 3 s; TE 40 ms; flip angle 90°; field of view (FOV) 24 cm, slice thickness 5 mm, 22 slices). In two functional runs, 100 EPI volumes per condition were acquired in a 10-cycle boxcar design with 15 s active/15 s rest. T1-weighted structural images were further acquired for each participant (matrix size $256 \times 256 \times 123$, slice thickness 1.6 mm with in-plane resolution 0.78×0.78).

Statistical analysis was performed with SPM2 (*http://www.fil.ion.ucl.ac.uk/spm/*). The raw data were converted to SPM compatible 'Analyze' format using the GE2SPM routine (*http://dbic.dartmouth.edu/~inati/tools/ge2spm.php*). For preprocessing, the anterior commissure was manually set as the origin of the functional images. Volumes were realigned to correct for motion artefacts, normalized to the MNI EPI-template and spatially smoothed with a Gaussian kernel (full width at half maximum, FWHM=6 mm).

For each condition the boxcar function was convolved with the haemodynamic response function using the general linear model. Low frequency noise was eliminated by a 60 s high-pass filter. For each individual, four contrasts, the condition contrasts ATTEND ('attend-rest') and IGNORE ('ignore-rest'), and the interaction contrasts ATTEND–IGNORE [(attend-rest)–(ignore-rest)] and IGNORE–ATTEND [(ignore-rest)–(attend-rest)], were calculated and submitted to a second-level random effects analysis of variance to test for significant group effects. Statistical significance was estimated voxel-by-voxel with a probability criterion of $P<0.005$ corrected for multiple comparisons, and a spatial extend threshold of 20 voxels (160 mm^3) was used to account for the possibility of false positives. Attention-modulated regions were identified in the interaction contrast. We further analysed the dynamics of activation in these areas by calculating Pearson correlations between (i) the timecourses of the cerebral activations and (ii) the convoluted boxcar function representing the design matrix, for the interaction contrast and the condition contrasts, respectively.

Results

Performance in the tactile discrimination task associated with the attend condition was good and all participants achieved at least 85% correct responses. The verbal accounts of the backward subtraction task associated with the ignore condition further indicated that participants engaged in the mental arithmetic.

To ascertain that our stimulation method produced reliable activations in the somatosensory system, we performed a basic region of interest analysis for areas SI and SII for each condition contrast. This data revealed robust activations in contralateral SI and bilateral SII for both conditions, with significant activations in each participant (Fig. 1).

Analysis of the critical ATTEND–IGNORE contrast revealed significant condition differences in the following regions: (i) contralateral primary somatosensory cortex (SI), (ii) ipsilateral secondary somatosensory cortex (SII), (iii) ipsi- and contralateral middle temporal gyrus (MTG; Table 1). The reverse IGNORE–ATTEND contrast was insignificant. Visual inspection of the timecourses for the attention-modulated regions further indicated that the BOLD response was greatest in contralateral SI. Thereby, the modulation of the %-signal change index is well synchronized with the haemodynamic function in the general linear model, which is also reflected in a significant positive correlation (see Table 1). Most critically, the amplitude of the SI–BOLD response is systematically higher when the tactile events are attended. In the ignore condition, tactile events clearly activate contralateral SI; however, the initial BOLD amplitude peak is lower and drops to near baseline level very quickly.

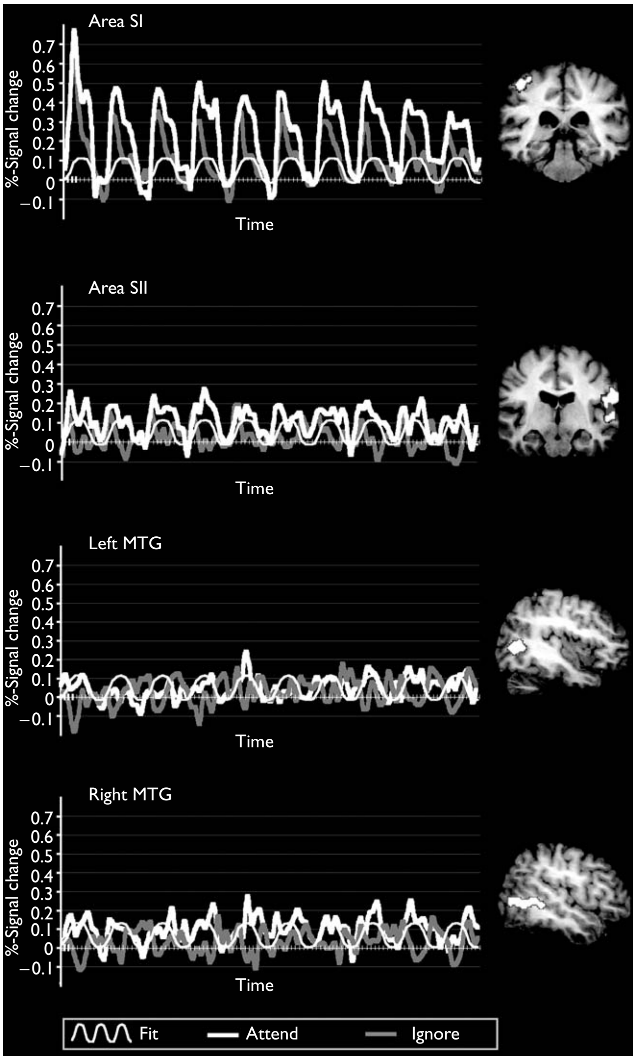

Fig. 1 Shows the brain regions identified in the interaction contrast ATTEND–IGNORE [(attend-rest)–(ignore-rest)] as being significantly modulated by attention, and the average timecourse of the blood oxygenation level-dependent (BOLD) response. For each region, the timecourses for the attend and ignore conditions are presented in relation to the convoluted boxcar function (design matrix). The *y*-axis depicts the %-signal change, the *x*-axis represents the number of scans. The BOLD in the contralateral primary somatosensory cortex is most strongly modulated by attention and the overall greatest activity is evoked when the tactile stimuli are attended.

A different picture emerges for SII and MTG. In these areas, the correlation between %-signal change and stimulus function is negative when stimuli are ignored. Thus, the BOLD response is lower during stimulation than during the resting baseline when stimuli are task-irrelevant. At the same time, these regions show a positive correlation when stimuli are attended. This suggests that attention modulates these areas differentially.

Discussion

The present experiment investigated whether top-down attention mechanisms induce changes in information processing in the primary somatosensory cortex that are measurable with fMRI. For this purpose, we chose an oddball paradigm that included a task in both attention conditions to ensure identical physical stimulus parameters, and to introduce some control over the attentional focus by actively disengaging attention from the tactile stimuli through a distractor task. Owing to the repeated measures design, we tested 20 participants and used a random effects model to identify condition differences in the BOLD response of the interaction contrast across the whole brain. This analysis revealed three areas, primary and secondary somatosensory cortex and the middle temporal gyri, in which activation changed significantly with attention.

Most critically, a clear activation increase with attention was found in contralateral SI. Moreover, the attentional modulation of the BOLD response was much greater in SI than in the other attention-modulated regions, most notably area SII. This result provides strong evidence for the idea that SI is susceptible to attentional modulation and further conforms to the theory that top-down attention mechanisms affect stimulus processing in primary cortices. Thus, directing attention to the tactile domain increases the activity in the primary somatosensory cortex, and presumably reflects a facilitation of afferent input processing. In line with this hypothesis we found a substantial increase in the %-signal change index when attention was focused on the tactile events. At the same time, ignored tactile events clearly activated the contralateral SI but this activation was much weaker. The timecourse of the SI-BOLD response further revealed that the signal was not only stronger for attended stimuli, but also maintained for longer before returning back to baseline. For ignored tactile events, however, the signal deflection was characterized by a sharp rise that quickly dropped back to baseline level. These observations suggest that attention may affect not only the signal amplitude but also the temporal dynamics of the neural activations reflected in the BOLD response. Potentially, these condition differences in the timecourse are very interesting. Owing to the low temporal resolution of fMRI, however, experiments with methods of higher temporal resolution will be necessary to further investigate whether and how the temporal characteristics of the BOLD response change with attention and how this relates to the actual firing pattern of cortical neurons.

Attentional modulations were further found for ipsilateral SII. Contralateral SII activation was clearly evident in all participants, but the signal intensity was not different between the two conditions. Interestingly, the attentional changes observed in the ipsilateral SII showed a different pattern to the changes found for SI. Although the latter was characterized by an increase of activity in both conditions and overall higher activities in the attend condition, the SII-BOLD response was increased when the tactile events were attended, but tended to decrease below baseline level when the tactile events were ignored. The timecourse mirrored this activity pattern in that it correlated positively with the stimulus function when stimuli were attended but negatively when stimuli were ignored. Statistically, the latter only reached trend level and the relevance of this finding is hence disputable. One potential mechanism, however, underlying the negative correlation in the ignore condition may be an active inhibition of this region when the tactile events are irrelevant. Interesting in this context is a recent study by Inoue and colleagues [21], which found opposite habituation effects for ipsilateral and contralateral SII. On the basis of these findings the authors proposed that the two

Table 1 Local cluster level maxima for significant activations in the ATTEND–IGNORE [(attend-rest)–(ignore-rest)] interaction contrast, and their time-course correlations

Region[a]	Estimated[b]		Coordinates[c]			Correlation coefficient[d]		
	Size	z-score	x	y	z	Attend	Ignore	Interaction
Left SI	219	4.0	−44	−26	55	0.8 $P<0.001$	0.6 $P<0.001$	0.7 $P<0.001$
Right SII	570	4.9	63	−16	23	0.6 $P<0.001$	−0.3 $P<0.05$	0.7 $P<0.001$
Left MTG	251	4.9	−42	−72	7	0.4 $P<0.001$	−0.6 $P<0.001$	0.7 $P<0.001$
Right MTG	539	3.9	50	−62	3	0.4 $P<0.001$	−0.5 $P<0.001$	0.6 $P<0.001$

[a]SI, primary somatosensory cortex; SII, secondary somatosensory cortex; MTG, middle temporal gyrus.
[b]Size, number of above-threshold voxels; z-score, peak activation in clusters of at least 20 voxels in which the %-signal change exceeds the extended threshold of $P<0.005$.
[c]Coordinates from the stereotaxic atlas of Talairach and Tournoux (1988).
[d]Correlation coefficients between hemodynamic response and stimulus function.

SII cortices may have different functional roles, a theory which could explain the differential SII attention effects found in this study.

Finally, we found bilateral activations in the MTG area. Like SII these activations were characterized by an increased BOLD response for attended stimuli but a decreased BOLD response for ignored stimuli. MTG activity has been associated with a wide variety of tasks, including complex visual processing such as viewing different emotional contents in films [22], multimodal sensory integration as for example bimodal audiovisual speech reading [23], and involuntary attention [24]. It hence appears that MTG is a multifunctional area, generally involved in higher cognitive processing. Attention mechanisms may well be one of the key processes associated with this region; however, further research is clearly necessary to enable this conclusion to be drawn.

Conclusion

Random effects analysis showed that activations in the primary somatosensory cortex are different when tactile stimuli are attended than when they are ignored. As we chose identical stimulus characteristics across conditions, these activation differences can be ascribed to attention and most likely reflect changed neural processing mediated through top-down mechanisms.

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