Université de Montréal

Représentation corticale de la mémoire à court-terme tactile chez l'humain pour une stimulation de la main : étude par magnétoencéphalographie

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Ce mémoire intitulé :

Représentation corticale de la mémoire à court-terme tactile chez l'humain pour une stimulation de la main : étude par magnétoencéphalographie

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L'activité cérébrale, reliée spécifiquement à la rétention d'information en mémoire à court-terme tactile, a été investiguée à l'aide de l'enregistrement des champs magnétiques produits par l'activité neuronale générée durant la période de rétention par une tâche de mémoire tactile. Une, deux, trois ou quatre positions, sur une possibilité de huit sur les phalangines et les phalangettes, de la main gauche ou droite, lors de blocs d'essai différents, ont été stimulées simultanément. Le patron de stimulation tactile devait être retenu pendant 1800 ms avant d'être comparé avec un patron test qui était, soit identique, soit différent par une seule position. Nos analyses se sont concentrées sur les régions du cerveau qui montraient une augmentation monotone du niveau d'activité soutenu durant la période de rétention pour un nombre croissant de positions à retenir dans le patron de stimulation. Ces régions ont plus de chance de participer à la rétention active de l'information à maintenir en mémoire à court-terme tactile. Le gyrus cingulaire (BA32), le gyrus frontal supérieur droit (BA 8), le precuneus gauche (BA 7, 19), le gyrus postcentral gauche (BA 7), le gyrus precentral droit (BA 6), le gyrus frontal supérieur gauche (BA 6) et le lobule pariétal inférieur droit (BA 40) semblent tous impliqués dans un réseau mnésique qui maintient les informations sensorielles tactiles dans un système de mémoire à court-terme spécialisé pour l'information tactile.

Mots clés: Mémoire à court-terme tactile, Magnétoencéphalographie

Brain activity specifically related to the maintenance of information held in tactile short-term memory was investigated, using recordings of magnetic fields from a whole-head magnetometer. This neuronal activity was measured during the retention interval of a tactile memory task. One, two, three, or four locations on distal and intermediate phalanges, out of eight positions, were simultaneously stimulated on the left or right hand in different blocks of trials. The tactile stimulation pattern was held in memory for 1800 ms before being compared with a test pattern that was either the same or different by one location. Our analyses focused on regions in the brain that showed a monotonic increase of the sustained activity levels during the retention interval with an increasing number of stimulated locations in the to-be-remembered pattern. These regions are the most likely to participate in the active retention of the information to be held in tactile sensory memory. The right cingular gyrus (BA 32), the right superior frontal gyrus (BA 8), the left precuneus (BA 7, 19), the left postcentral gyrus (BA 7), the right precentral gyrus (BA 6), the left superior frontal gyrus (BA 6) and the right inferior parietal lobule (BA 40) all appear to be involved in a memory system that maintains tactile sensory input in a short-term memory system specialized for tactile information.

Key words : Tactile short-term memory, Magnetoencephalography

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Liste des sigles et abbréviations

ASTM : Auditory Short-Term Memory : Mémoire à court-terme auditive

DMS : Delayed Match to Sample task : tâche de comparaison retardée

MEG : Magnetoencephalograph : Magnétoencéphalographe

MRI : Magnetic Resonance Imagery : IRM : Imagerie par résonance magnétique

S1 : Primary Somatosensory Cortex : Cortex somatosensoriel primaire

S2 : Secondary Somatosensory Cortex : Cortex somatosensoriel secondaire

STM : Short-Term Memory : Mémoire à court-terme

TMS : Transcranial Magnetic Stimulation : Stimulation magnétique transcranienne

TSTM : Tactile Short-Term Memory : Mémoire à court-terme tactile

VSTM : Visual Short-Term Memory : Mémoire à court-terme visuelle

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Avant-propos

La mémoire à court-terme tactile (TSTM) est la capacité qui nous permet d'encoder, de maintenir pendant quelques secondes et, enfin, de récupérer les informations contenues dans une stimulation mécanique appliquée sur la peau. Cela nous permet de se rappeler si nous avons déjà été touché à un endroit ou de reconnaître si un patron de points de pression appliqués à la main est identique ou différent d'un autre. Les résultats de recherche sur la mémoire à court-terme dans différentes modalités suggèrent l'implication, pour chaque modalité, d'un réseau cortical spécialisé(Auditif (ASTM), Grimault, Lefebvre, Vachon, Peretz, Zatorre, Robitaille & Jolicoeur, 2009a; Visuel (VSTM), Grimault, Robitaille, Grova, Lina, Dubarry & Jolicoeur, 2009b; TSTM, Hegner *et al.*, 2007a; Hegner *et al.*, 2007b; Numminen *et al.*, 2004; Preuschhof *et al.*, 2006; STM, Klingberg, Kawashima & Roland, 1996; Ricciardi *et al.*, 2006). Ces réseaux sont typiquement composés d'aires sensorielles spécifiques, d'aires associatives inter-modalité, ainsi que d'aires frontales de contrôle. Pour une stimulation de la main, l'information sensorielle atteint d'abords le cortex à l'aire somatosensorielle primaire (S1), sur le gyrus postcentral, du côté controlatéral à la main stimulée. L'information atteint ensuite, de manière bilatérale et pratiquement simultanée, les aires somatosensorielles secondaires (S2), situées dans les opercules pariétales. Les aires somatosensorielles secondaires projettent à leur tour vers les aires motrices et prémotrices, les aires associatives du cortex pariétal supérieur et, par l'intermédiaire de l'insula, les aires frontales et parahippocampiques (Burton *et al.*, 1995).

En ce qui concerne la mémoire, certaines aires du parcours de l'information

somatosensorielle ont attiré d'avantage l'attention que les autres, nomément S1 et S2. Burton et Sinclair (2000) ont rapporté que des expériences de mémoire à court-terme utilisant des stimuli vibrotactiles n'avaient pas trouvé de signes de mémoire dans S1 et S2 au delà d'une courte mémoire sensorielle. La rétention de stimuli vibrotactiles durant une tâche de mémoire n'est pas perturbée par une stimulation magnétique transcranienne (TMS) appliquée au S1 controlatéral, 900 ms après la stimulation, ou au S1 ipsilatéral, à aucun moment (Harris *et al.*, 2002). De plus, les activations dépendantes de la fréquence dans S2 s'estompent 500 ms après la fin de la stimulation chez les primates (Burton & Sinclair, 2000). Cependant, un effet de mémoire a été observé, dans S1 chez les primates, pour une tâche de comparaison retardée (DMS) effectuée par l'exploration tactile de cylindres à texture variable (Zhou & Fuster, 1996).

Pour S2, sa connection réciproque au cortex frontal, ainsi qu'au cortex pariétal en fait une candidate plausible pour une implication en STM. Bien que son rôle en STM ait tout d'abord été suggéré par des études liant des lésions de S2 à une diminution de la reconnaissance tactile des objets (Carlson, 1990; Horster & Ettlinger, 1987; Murray & Mishkin, 1984), de plus récentes études en imagerie ont confirmé son implication en STM (Bonda, Petrides & Evans, 1996; Preuschhof *et al.*, 2006). Pourtant, S2 semble être plus impliqué au niveau de la prise de décision que durant la rétention de l'information en mémoire (Preuschhof *et al.*, 2006; Romo *et al.*, 2002). D'autres régions ont été révélées lors d'expériences en IRMf sur la reconnaissance tactile et la STM dans la modalité tactile, nomément le precuneus, le gyrus cingulaire, les gyrus frontaux inférieur et supérieur et le

lobule pariétal inférieur (Klingberg *et al.,* 1996; Numinen *et al.,* 2004; Preuschhof *et al.,* 2006; Reed *et al.,* 2005). Ces régions représentent un réseau de haut niveau du cerveau qui pourrait être lié à des fonctions complexes. Elles sont probablement impliquées dans l'encodage et la récupération de l'information, en plus de sa rétention.

Dans l'article inclus dans le présent mémoire, nous nous sommes concentrés sur les régions corticales qui participent à la rétention à court-terme des informations tactiles (TSTM). Pour parvenir à isoler les régions qui sont les meilleures candidates comme sites de la TSTM, nous avons analysé le niveau d'activité corticale et nous avons isolé les régions dont le niveau d'activité augmente en fonction de l'augmentation de la charge mnésique pendant la rétention d'information tactile. Cette approche présuppose que les régions corticales directement impliquées en TSTM auront à augmenter leur niveau d'activité pour maintenir une plus grande quantité d'information. Une approche similaire a été utilisée avec succès pour les modalités visuelle et auditive (Todd & Marois, 2004; Vogel & Machizawa, 2004; Grimault, Robitaille, Grova, Lina, Dubarry & Jolicoeur, 2009b; Grimault, Lefebvre, Vachon, Peretz, Zatorre, Robitaille & Jolicoeur, 2009a). Nous avons utilisé la magnétoencéphalographie (MEG) pour enregistrer l'activité cérébrale pendant la période de rétention d'une tâche de mémoire tactile qui comportait quatre niveaux de charge mnésique. La manipulation paramétrique de la charge mnésique nous a permis d'identifier un petit nombre de régions dont l'activité soutenue au cours de la période de rétention augmentait avec une plus grande charge mnésique, suggérant une implication possible dans la rétention de l'information tactile. Étant donné la haute résolution temporelle de la MEG,

nous pouvons être confiants que l'activité sur laquelle nous avons fondé notre analyse représente bien la rétention de l'information, plutôt que l'encodage ou la récupération, car nous avons analysé les patrons d'activation soutenus sur une période débutant longtemps après la réponse évoquée initiale et se terminant avant la présentation du stimulus test. L'analyse des niveaux d'activité précédant la présentation des stimuli test nous assure de ne pas confondre dans notre mesure l'activité générée par la récupération, la comparaison, la décision et la réponse. En conséquence, cette technique nous a permis d'explorer le réseau des régions impliquées durant la rétention d'information tactile et ce, de manière plus spécifique que dans les recherches antérieures.

Cortical representation of tactile short-term memory in the human brain for stimulation patterns on the hand: Evidence from magneto-encephalography

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Running head: MEG investigation of tactile short-term memory

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Brain activity specifically related to the maintenance of information held in tactile short-term memory was investigated, using recordings of magnetic fields from a whole-head magnetometer. This neuronal activity was measured during the retention interval of a tactile memory task. Our analyses focused on regions in the brain that showed a monotonic increase of the sustained activity levels during the retention interval with an increasing number of stimulated locations in the to-be-remembered pattern. These regions are the most likely to participate in the active retention of the information to be held in tactile sensory memory. The right cingular gyrus, the right superior frontal gyrus, the left precuneus, the left postcentral gyrus, the right precentral gyrus, the left superior frontal gyrus and the right inferior parietal lobule all appear to be involved in the maintenance of tactile sensory input in a specialized short-term memory system.

Tactile short term memory(TSTM) is the capacity that allows us to encode, maintain for a few seconds, and then retrieve the properties of a mechanical stimulation delivered to the skin. This enables us to remember if we have already been touched somewhere or to recognize a pattern of pressure points applied to the hand and determine if another pattern is identical or different. Research findings on short-term memory from the different modalities suggest the involvement, for each modality, of specific cortical networks (Auditory (ASTM), Grimault, Lefebvre, Vachon, Peretz, Zatorre, Robitaille & Jolicoeur, 2009a; Visual (VSTM), Grimault, Robitaille, Grova, Lina, Dubarry & Jolicoeur, 2009b; TSTM, Hegner *et al.*, 2007a; Hegner *et al.*, 2007b; Numminen *et al.*, 2004; Preuschhof *et al.*, 2006; STM, Klingberg, Kawashima & Roland, 1996; Ricciardi *et al.*, 2006). These networks are typically constituted of sensory specific areas, cross-modality associative areas and frontal control areas. For a stimulation to the hand, the sensory information first reaches the cortex at the primary somatosensory area (S1), on the postcentral gyrus, contralateral to the hand stimulated. The information then reaches, bilaterally and nearly simultaneously, the secondary somatosensory areas (S2), located in the lateral opercula. The secondary somatosensory areas project in turn to motor and premotor areas, to associative areas in the superior parietal area, as well as, through the insula, to the frontal and parahippocampal areas (Burton *et al.*, 1995).

In terms of memory, certain areas of the somatosensory pathway have attracted more attention than others in the tactile modality, namely S1 and S2. Burton and Sinclair (2000) reported that STM experiments using vibrotactile stimuli did not find any sign of

memory in S1 or S2 beyond brief sensory memory. The retention of vibrotactile stimuli, during a memory task, was not disrupted by a transcranial magnetic stimulation (TMS) pulse applied to contralateral S1, 900 ms after stimulation, or to ipsilateral S1 at any delay (Harris *et al.*, 2002). Also, frequency-selective activations in S2 faded 500 ms after the end of the stimulation in primates (Burton & Sinclair, 2000). Haptically explored rods with varying surface texture in a delayed matching to sample task did, however, produce a memory effect in S1 for primates (Zhou & Fuster, 1996).

For S2, its reciprocal connectivity to parietal and frontal cortex make it a plausible candidate for an involvement in STM. Although its role in STM was suggested by studies linking S2 lesions to impaired tactile recognition of objects (Carlson, 1990; Horster & Ettlinger, 1987; Murray & Mishkin, 1984), more recent imaging studies have confirmed its implication in STM (Bonda, Petrides & Evans, 1996; Preuschhof *et al.*, 2006). However, S2 seems more implicated at the decision making stage than during the maintenance of the information in memory (Preuschhof *et al.*, 2006; Romo *et al.*, 2002). Other regions have been revealed in fMRI experiments of tactile recognition and STM in the tactile modality, namely the precuneus, the cingulate gyrus, the superior and inferior frontal gyrus and, the inferior parietal lobule (Klingberg *et al.,* 1996; Numinen *et al.,* 2004; Preuschhof *et al.,* 2006; Reed *et al.,* 2005). These regions represent the higher order connectivity network of the brain, usually linked to complex functions. They are possibly implicated in the encoding as well as the retrieval of the information in addition to retention.

In the present article, we focused on the cortical regions that are likely to participate in the short-term retention of tactile information (TSTM). In order to isolate regions that are particularly good candidates as key sites for TSTM, we looked for cortical regions with activity levels that increased with memory load, during the retention of tactile information. This approach works under the assumption that cortical regions directly involved in TSTM will have to increase their level of activity to reflect the increase in information to be retained. A similar approach has been successfully used for visual and auditory modalities (Todd & Marois, 2004; Vogel & Machizawa, 2004; Grimault, Robitaille, Grova, Lina, Dubarry & Jolicoeur, 2009b; Grimault, Lefebvre, Vachon, Peretz, Zatorre, Robitaille & Jolicoeur, 2009a). We used magnetoencephalography (MEG) to record brain activity during the retention interval of a tactile memory task in which we used four levels of memory load. The parametric manipulation of memory load allowed us to identify a small number of cortical regions that had sustained activity levels that increased with load, suggesting a possible involvement in the retention of tactile information. Given the high temporal resolution of MEG, we could be confident that the activity we focused on reflected the retention of information, rather than encoding or retrieval, because we analyzed patterns of sustained activity, long after the initial evoked responses, and before the test stimuli were presented. The analysis of activity levels prior to the presentation of test stimuli ensures that the analyzed activity does not encompass retrieval, comparison, decision, or response-related activity. Consequently, this technique enabled us to explore the network of regions implicated in the retention of tactile information, and with a greater specificity than in previous research.

Method

Participants

Two participants, one man (age 21) and one woman (age 25), were each tested in multiple sessions. Both were right handed and neither had a history of neurological problems or concussion.

Material

We measured magnetic fields using a CTF275 whole-head magnetoencephalograph with 271 working channels at a sampling rate of 600 Hz, with synthetic third-order gradiometer noise correction (Vrba & Robinson, 2001) in a magnetically-shielded testing room. Visual feedback was back-projected onto a translucent screen by a data projector located outside the shielded room. The tactile stimulations were delivered with a magnetically neutral pneumatic stimulator with 8 independent finger clips placed on a single hand during each session (Mertens & Lütkenhöner, 2000). Clips were affixed to the first and second phalanges of each finger except the thumb. Stimulation was produced by the rise of a supple membrane displaced by a brief change in air pressure (100 ms stimulation). Although the tactile stimulator was located outside the shielded room, the stimulator could be heard from inside. Earplugs were used to render this faint sound inaudible.

Experimental Procedure

Participants were tested in a supine position in the magnetoencephalograph with

their stimulated hand resting at their side. They had to give their answers with the non-stimulated hand. Each trial began with the presentation of previous trial feedback on their accuracy for 1900 ms then followed by a 500 ms mean delay period with a 100 ms jitter (400−600 ms). Each trial, as illustrated in Figure 1, had two tactile stimulation patterns, each presented for about 100 ms, consisting of a number of positions, varying from one to four (the load manipulation), selected at random from the eight possible locations, and activated simultaneously. The memory pattern was presented first and followed by an empty retention period of 1800 ms. Following the retention interval, a test stimulation, identical or different by a single position, was presented. The task was to determine whether the two stimulation patterns were identical or different. The response had to be given in under 1900 ms from the onset of the presentation of the test stimulation. Finally, an intertrial interval of 400 ms was added after the response. Each experimental block of trials contained an equal number of the eight trial types (same vs different X load) in random order. Each participant completed 8 sessions, performed on different days; 4 with right-hand stimulation and 4 with left-hand stimulation. Each session had a single practice block of 24 trials followed by 800 experimental trials presented in 10 blocks of 80. Thus, each participant performed 6400 experimental trials, 3200 for each hand.

Insert Figure 1 about here.

In addition to MEG data, collected at a sampling rate of 600 Hz, EEG data was collected from bipolar electrodes positioned at the outer canthi of the eyes, for the horizontal electro-oculogram (HEOG), and above and below the left eye for the vertical electro-oculogram (VEOG).

Analyses

For each session, magnetic field data received a third order gradiometer noise correction and was baseline corrected based on the mean during the 200 ms prior to the presentation of the memory stimulation pattern. Electro-oculograms were visually inspected for eye blinks and eye movements. Between 500 and 750 trials were kept out of a possible 800 for each session. The number of trials retained for analysis can be broken down as follows: first participant (5343) and second participant (4589); left hand stimulation (5141) and right hand stimulation (4791); load one (2421), load two (2473), load three (2485), and load four (2553). The magnetic field data was co-registered to the participant's anatomical MRI (T1) brain scan using three fiducials coils placed at the nasion, the left, and right ear, as well as points digitized from the participant scalp surface with a Polhemus Fastrak digitizer.

Source localization was performed using the erSAM algorithm (Cheyne *et al*., 2006). Maps of source activation power were produced for each load × session × participant combination for the retention period between 1000 ms and 1800 ms using the full range of frequency at a resolution of 2 mm and a 200 ms pretrial baseline. They were then imported to the stereotaxic Talairach space. The individual maps were analyzed with a general linear model (GLM) and regressed against the average K value of the participants. The K value is an estimate of the number of representations retained in memory that is calculated from the performance at each memory load (Cowan, 2001). This method seeks to find the cortical locations that best correlate with the behavioral results of greatest relevance to the study, in

this case the number of tactile representations held in TSTM. Participant and Stimulation Side regressors were also used to remove their variability from the resulting localization. Positive peaks on the *t*-stat maps were further analyzed to gain better insight. Cortical locations, in the GLM analysis demonstrating a significant correlation with load, were converted back to the participant space for time course calculation using the erSAM algorithm for each participant and session. For this calculation, the orientation of the equivalent dipole for a given virtual electrode at a given position was held constant across loads, hands, and sessions for each participant. For each position and each individual trial, the average value of the virtual electrode in pseudo-Z units was computed for each load for the period between 1000 ms and 1800 ms from the onset of the memory pattern stimulation. Each averaged activation value in pseudo-Z units was treated as an independent sample in an analysis of variance Stimulation Side × Participant × Load. Bonferonni corrections were applied to post hoc test for multiple comparisons.

Results

Figure 2 shows the results of the GLM regression analysis. Areas shown in this map are those with a significant positive correlation between observed sustained brain activity and estimated memory load during the retention period. The GLM *t*-Stats map shows activations increasing with the load in the right cingular gyrus (BA 32), the right superior frontal gyrus (BA 8), the left precuneus (BA 7, 19), the left postcentral gyrus (BA 7), the right precentral gyrus (BA 6), the left superior frontal gyrus (BA 6), and the right inferior parietal lobule (BA 40).

Insert Figure 2 about here.

Analysis of variance tests for a Load × Side × Participant model performed at the peaks of those regions showed numerous differences in the activation pattern between the participants which can be seen in detail in Table 1. Results not shown were not reaching a significance level of $p < .05$. The right cingular gyrus activation (2) showed an interaction Load × Participant, $F(3, 9924) = 3.132$, $p < .025$, $R^2 = .001$, and a Load main effect, $F(3, 9924) = 16.279$, $p < .001$, $R^2 = .005$. The right superior frontal gyrus activation (3) showed an interaction Load × Participant $F(3, 9924) = 7.941$, $p < .001$, $R^2 = .002$, and a Load main effect, $F(3, 9924) = 34.712$, $p < .001$, $R^2 = .01$. For those two regions (2, 3), both participants showed the same trend of load increasing effect, but participant 2 showed a stronger statistical effect. Only participant 2 showed significant load increase effects for the left precuneus activation (1), with an interaction Load × Side × Participant, $F(3, 9924) = 3.486$, $p < .015$, $R^2 = .001$, an interaction Load × Participant, $F(3, 9924) = 3.899$, $p < .009$, $R^2 = .001$, and a Load main effect, $F(3, 9924) = 8.219$, $p < .001$, $R^2 = .002$, as well as for the right inferior parietal lobule activation (4), with an interaction Load × Participant, $F(3, 9924) = 15.361$, $p < .001$, $R^2 = .005$, and a Load main effect $F(3, 9924) = 11.136$, $p < .001$, $R^2 = .003$. The remaining regions did not reveal the same unambiguous increase in activity across participants or stimulated hands. The right precentral gyrus activation (5) showed an interaction load × participant $F(3, 9924) = 22.722$, $p < .001$, $R^2 = .007$, and a Load main effect, $F(3, 9924) = 5.682$, $p < .001$, $R^2 = .002$. The left superior frontal gyrus activation (6) showed an interaction Load × Participant $F(3, 9924) = 39.940$, $p < .001$, $R^2 = .012$, and a Load main effect, $F(3, 9924) = 29.430$, $p < .001$, $R^2 = .009$. Both these regions showed a

monotonic increase of load activation for participant 2 while the means of activation by load for participant 1 were more erratic leading to a partial cancellation of the effect across participants. The right postcentral gyrus activation (7) showed an interaction Load × Side × Participant, $F(3, 9924) = 2.802$, $p < .038$, $R^2 = .001$, an interaction Load × Participant, $F(3, 9924) = 3.941$, $p < .008$, $R^2 = .001$, and a Load main effect, $F(3, 9924) = 7.818$, $p < .001$, $R^2 = .002$. Only participant 2 had an increase of load related activity in this region with a stronger effect for right hand stimulations. All regions overall showed a main effect of load which can be seen in Figure 3.

Insert Figure 3 about here.

Discussion

The main goal of this work was to identify cortical regions that are likely to participate in the maintenance of tactile information in TSTM. The way we managed to isolate TSTM during retention was to manipulate the memory load in a task where the participants were submitted to brief patterns of simultaneous pressure points on the fingers of the right or left hand. An increased number of pressure points in the stimulation pattern was expected to produce a higher load on TSTM and, as a side effect, produce higher sustained activation levels at the cortical locations related to the retention of information in TSTM. We adopted a strategy devised to obtain stable results on a small pool of participants by testing them thoroughly (8 sessions of 800 trials), this, in order to better sort out what happens in individuals rather than lose the details in a group analysis. The strategy was essentially successful, in the fact that, we could make out a few cortical regions that showed similarly monotonic increases in activation related to memory load in both

participants. However, some cortical regions showed individual differences in activation pattern that will need to be examined in further research. Those differences could arise from strategic differences for the task or from more fundamental and individual structural differences.

The most promising regions for their involvement in TSTM in both participants are the right cingulate gyrus and the right superior frontal gyrus. Both revealed the same increase in activation correlated to the value of K, as well as, showing significant load effects for both participants. Although, those are the only cortical regions to reveal such a clear picture, other regions are more than likely to participate to TSTM on the basis of the monotonic increases in activation related to memory load demonstrated by participant 2 for every region of interest revealed by the GLM regression. The left precuneus, the right inferior parietal lobule, the left superior frontal gyrus, and the right postcentral gyrus do all demonstrate nice monotonic increases of activity with increased load for participant 2 and should be kept on the short list of regions of interest.

Most regions of interest in parietal and frontal cortex are located on the right hemisphere which lead us to question the inter-hemispheric equilibrium of activation in tactile STM. While visual and auditory perceptual systems are essentially similar and mirrored for both hemispheres, the somato-motor system is notoriously behaviorally unbalanced. Since both participants were right handed, there is a possibility that there might be some hemispheric specialization due to handedness in participants, though this could not

be confirmed based on the current results. While some cortical regions of interest showed Load × Side × Participant interaction, namely the left precuneus and the right postcentral gyrus, all other region did not show any interaction of load and stimulated hand. This finding is of interest because, while the initial cortical evoked response is clearly and solely contralateral to the stimulated hand, the retention of the tactile information in TSTM is, possibly, at some nodes of the implicated network, blind to the initial stimulation side. We can see this similitude across hand of stimulation during retention in Figure 4, which splits the output of virtual electrode 3 depending on which hand was stimulated.

Despite our expectation, S1 and S2 increases in activation did not follow the load increment pattern during the latter part of the retention interval. The somatotopic organization of these regions may result in a larger distribution of the activation across the cortex and their receptive fields may inhibit neighboring finger stimulations hiding a possible load effect. The regions we located are very similar to those revealed in fMRI by Numinen *et al.* (2004), Klingberg *et al.* (1996) for the tactile part of his experiment and Preuschhof *et al.* (2006) for the maintenance locations. This reinforces the confidence we have in those regions of interest. We can also observe a large overlap in our left precuneus activation and the one observed in visual STM by Grimault *et al*. (2009b), which would indicate a possible implication of this region across modalities in STM during retention.

Figure Captions

Figure 1. A memory stimulation pattern is presented for 100 ms to middle and distal phalanges of one hand, and then remembered for 1800 ms. Following the empty retention interval, a test stimulation pattern, that is either identical or different from the initial stimulation, is presented for 100 ms. The number of stimulated points (1, 2, 3, or 4) determines the memory load for that trial.

Figure 2. Statistical parametric maps (*t*-Statistics) of the activations increasing following the behavioral memory capacity of the participants, as represented by the K value, for each load. The threshold was set at a false discovery rate of $p < .001$. (1) left precuneus (BA 7; x = -18; y = -75; z = 36); (2) right cingulate gyrus (BA 32; x = 17; y = 5; z = 43); (3) right superior frontal gyrus (BA 8; x = 5; y = 25; z = 50); (4) right inferior parietal lobule (BA 40; x = 58; y = -30; z = 30); (5) right precentral gyrus (BA 6; x = 58; y = 1; z = 34); (6) left superior frontal gyrus (BA 6; x = -20; y = -12; z = 64); (7) right postcentral gyrus (BA 7; x = 12; y = -45; z = 72).

Figure 3. Activity at sites of interest in the maps from the GLM analysis (Figure 2) shown as a virtual electrode at that location (in pseudo-Z units) filtered at 6 Hz for display purposes. The virtual electrode number matches the location presented in Figure 2.

Figure 4. Activity at site 3 from the GLM analysis maps (Figure 2) split in function of the hand of stimulation. The left virtual electrode (in pseudo-Z units) represents trials which

stimulated the left hand and right virtual electrode represents trials which stimulated the right hand. Both virtual electrodes are filtered at 6 Hz for display purposes.

Figure 1

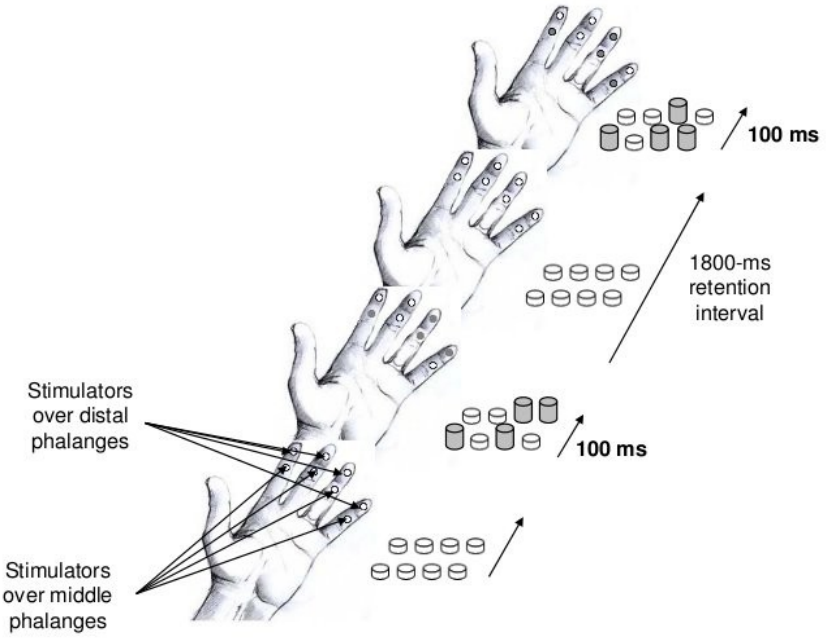
100 ms
1800-ms
retention
interval
Stimulators
over distal
phalanges
100 ms
Stimulators
over middle
phalanges

Figure 2

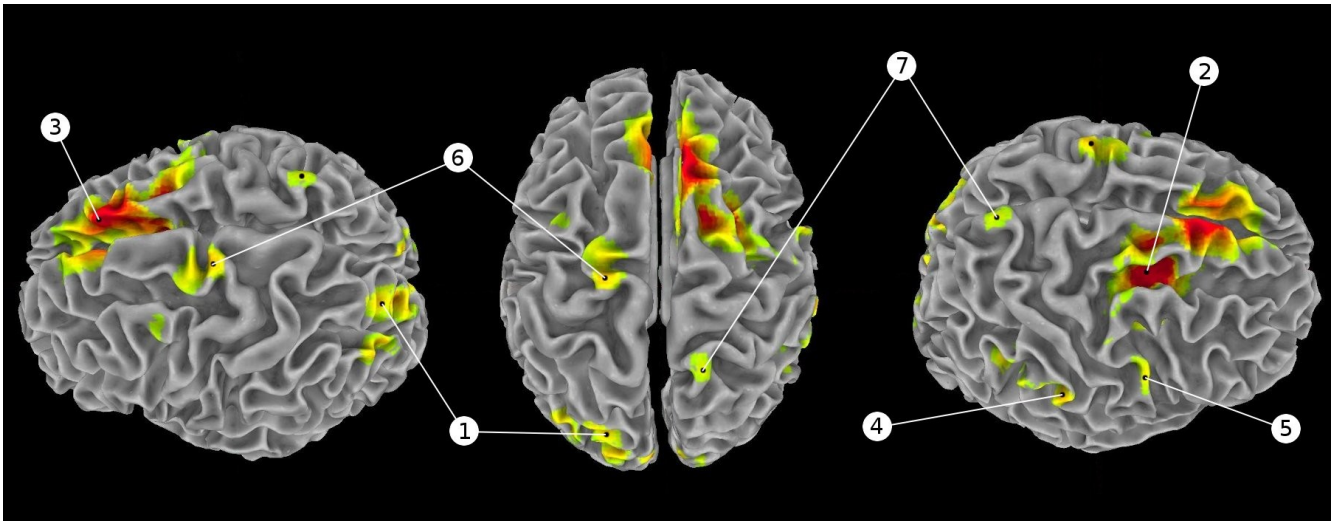

Figure 3

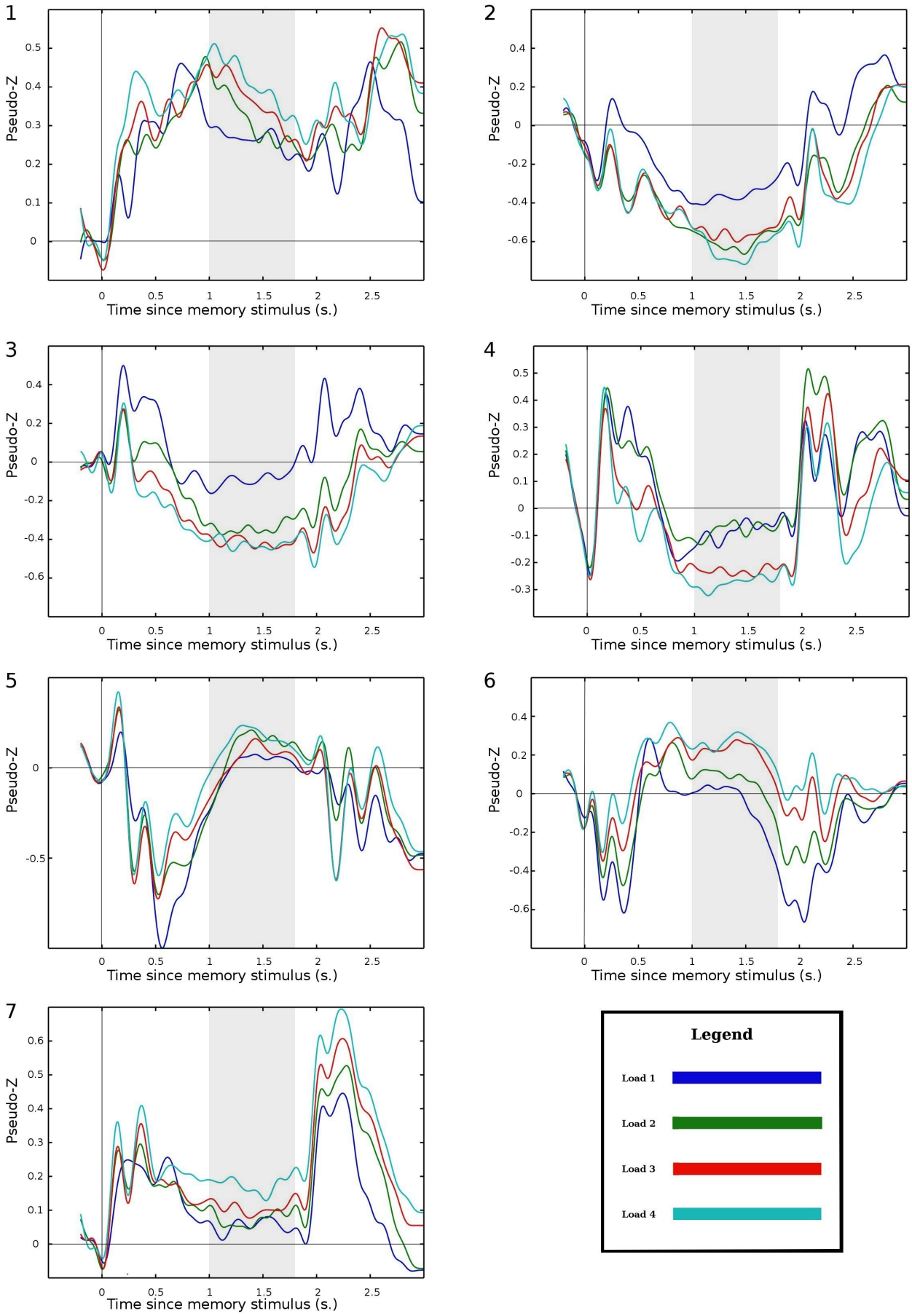
1
2
3
4
5
6
7
Pseudo-Z
Time since memory stimulus (s.)
Legend
Load 1
Load 2
Load 3
Load 4

Figure 4

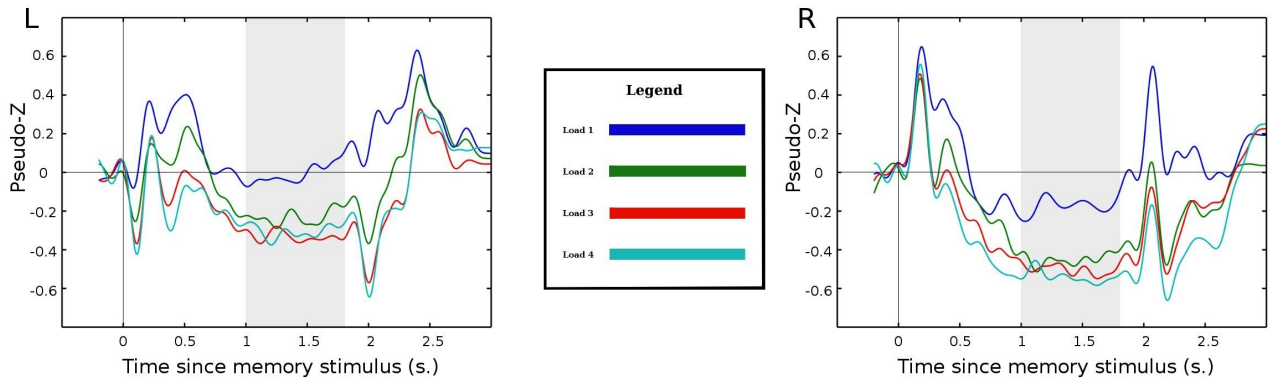
L
R
Pseudo-Z
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
0.5
1
1.5
2
2.5
Time since memory stimulus (s.)
Legend
Load 1
Load 2
Load 3
Load 4

Table 1. Summary by participant of mean activity by load recorded by virtual electrodes at regions of interest identified in Figure 2. Mean activity levels across participants are plotted in Figure 3.

Electrode	Participant	Mean and Std Deviation				F statistics
		load 1	load 2	load 3	load 4	
1	Participant 1	M = 0.2189 σ = 0.9975	M = 0.2216 σ = 1.0368	M = 0.2608 σ = 0.9774	M = 0.2669 σ = 1.0204	F(3, 9924) = 0.644, $p > .586$
	Participant 2	M = 0.2968 σ = 1.3171	M = 0.3976 σ = 1.2819	M = 0.4741 σ = 1.2913	M = 0.5564 σ = 1.3128	F(3, 9924) = 10.543, $p < .001$ ***
2	Participant 1	M = -0.3242 σ = 1.3013	M = -0.5606 σ = 1.27963	M = -0.5297 σ = 1.2916	M = -0.5043 σ = 1.3024	F(3, 9924) = 6.928, $p < .001$ ***
	Participant 2	M = -0.4067 σ = 1.6323	M = -0.6304 σ = 1.6800	M = -0.5914 σ = 1.6167	M = -0.7801 σ = 1.6142	F(3, 9924) = 12.634, $p < .001$ ***
3	Participant 1	M = -0.1565 σ = 1.2080	M = -0.3280 σ = 1.1644	M = -0.3299 σ = 1.1822	M = -0.3316 σ = 1.1824	F(3, 9924) = 5.773, $p < .001$ ***
	Participant 2	M = -0.0176 σ = 1.4276	M = -0.3466 σ = 1.4988	M = -0.5062 σ = 1.4384	M = -0.5161 σ = 1.3961	F(3, 9924) = 35.773, $p < .001$ ***
4	Participant 1	M = 0.0888 σ = 1.3278	M = 0.2051 σ = 1.3822	M = 0.1468 σ = 1.3187	M = 0.1739 σ = 1.3728	F(3, 9924) = 1.545, $p > .201$
	Participant 2	M = -0.2781 σ = 1.5275	M = -0.3633 σ = 1.5319	M = -0.6080 σ = 1.5411	M = -0.7115 σ = 1.5584	F(3, 9924) = 22.836, $p < .001$ ***
5	Participant 1	M = -0.0579 σ = 1.2419	M = -0.2325 σ = 1.2604	M = -0.2938 σ = 1.2243	M = -0.1345 σ = 1.2354	F(3, 9924) = 8.541, $p < .001$ ***
	Participant 2	M = 0.0832 σ = 1.3803	M = 0.4317 σ = 1.3964	M = 0.3989 σ = 1.3022	M = 0.4485 σ = 1.3775	F(3, 9924) = 19.942, $p < .001$ ***
6	Participant 1	M = 0.0451 σ = 1.2321	M = -0.1011 σ = 1.2087	M = -0.0563 σ = 1.2189	M = 0.0187 σ = 1.2194	F(3, 9924) = 3.661, $p < .012$ *
	Participant 2	M = -0.1824 σ = 1.3810	M = 0.1918 σ = 1.3499	M = 0.4510 σ = 1.3668	M = 0.4575 σ = 1.3007	F(3, 9924) = 62.639, $p < .001$ ***
7	Participant 1	M = -0.1345 σ = 0.9079	M = -0.1080 σ = 0.8657	M = -0.1325 σ = 0.9092	M = -0.0854 σ = 0.9320	F(3, 9924) = 0.736, $p > .530$
	Participant 2	M = 0.2279 σ = 1.0877	M = 0.2623 σ = 1.0989	M = 0.3438 σ = 1.0869	M = 0.4442 σ = 1.0624	F(3, 9924) = 10.904, $p < .001$ ***

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Conclusion

L'objectif principal de ce projet était d'identifier les régions corticales qui avaient le plus de chance de participer au maintien de l'information tactile en TSTM. Pour isoler les aires impliquées en TSTM pendant la rétention, nous avons manipulé la charge mnésique dans une tâche où le participant devait retenir un patron de points de pression qui lui étaient appliqués aux doigts d'une seule main. Un nombre plus élevé de points de pression dans le patron reçu devrait produire une charge plus grande de TSTM et, du même coup, produire une plus grande activation des aires corticales liées à la rétention d'information en TSTM. Nous avons opté pour une approche de type psychophysique, consistant à tester un grand nombre de fois (8 sessions de 800 essais) un petit nombre de participants dans le but d'obtenir des résultats d'une grande stabilité qui réflète mieux l'activité qui se retrouve chez un individu que de perdre les détails dans une étude de groupe. La stratégie a été un succès pour l'essentiel, car elle nous a permis de trouver quelques régions corticales qui montraient une augmentation monotone similaire chez les deux participants de l'activité lié à la charge mnésique. Cependant, quelques régions ont montré des différences de patron d'activation qui vont nécessiter de plus amples investigations. Ces différences pourraient provenir de différences de stratégie utilisée pour compléter la tâche ou encore de différences plus fondamentales issues des différences individuelles des structures impliquées.

Les régions les plus prometteuses pour leur implication en TSTM pour les deux participants sont le gyrus cingulaire droit et le gyrus frontal supérieur droit. Les deux régions révèlent la même augmentation de l'activité correlée à la valeur de K et montrent un

effet de charge mnésique significatif chez les deux participants. Cependant, les autres régions montrent un portrait plus ambigu; bien qu'elles participent fort possiblement à la TSTM, cette affirmation ne peut se faire qu'avec l'appui des augmentations monotones de l'activité relié à la charge mnésique observées chez le participant 2 pour toutes les régions d'intérêts révélées par la régression du GLM. Le precuneus gauche, le lobule pariétal inférieur droit, le gyrus frontal supérieur gauche et le gyrus postcentral droit montrent tous des augmentations monotones de l'activité lié à une augmentation de la charge mnésique pour le participant 2 et devraient être conservés comme régions d'intérêt.

La plupart des régions d'intérêt des cortex pariétal et frontal se retrouvent dans l'hémisphère droit ce qui nous mène à nous interroger sur l'équilibre inter-hémisphérique des activations en TSTM. Les systèmes sensoriels visuel et, de manière plus controversée, auditif sont essentiellement identiques entre chaque hémisphère, par contre, le système somato-moteur est connu pour la préférence manuelle comportementale. Comme les deux participants sont droitiers, il y a possiblement une spécialisation hémisphérique due à cette préférence manuelle, bien que ce ne soit pas possible de le confirmer avec les résultats actuels. Certaines régions d'intérêt ont montré une interaction Charge × Côté × Participant, nommément le precuneus gauche et le gyrus postcentral droit, pourtant toutes les autres regions n'ont montré aucune interaction entre la charge et la main stimulée. Cette information est d'intérêt car, bien que la réponse évoquée initiale au niveau du cortex soit clairement et seulement controlatérale à la main stimulée, la rétention d'information tactile en TSTM est, possiblement, à certains noeuds du réseau impliqué, aveugle au côté de

stimulation initial. Nous pouvons voir cette similitude entre les activations durant la rétention pour des stimulations de main différentes dans la Figure 4, qui divise les résultats obtenus à l'électrode 3 en fonction de la main stimulée.

Malgré nos attentes, les augmentations d'activité à S1 et S2 ne suivent pas l'augmentation de charge mnésique pendant la section de la période de rétention que nous avons analysé. L'organisation somatotopique de ces régions pourrait résulter en une plus grande distribution des activations au niveau du cortex et leurs champs récepteurs pourraient inhiber l'activité produite par la stimulation de doigts voisins, camoufflant un effet de charge mnésique. Les régions que nous avons identifié sont très semblables à celles révélées en IRMf par Numinen *et al.* (2004), Klingberg *et al.* (1996) pour la partie tactile de leur expérience et Preuschhof *et al.* (2006) pour les aires impliquées dans le maintien de l'information. Ceci renforce la confiance que nous pouvons avoir dans nos régions d'intérêt. On peut également observer un chevauchement important entre notre activation du precuneus gauche et celle observée en VSTM par Grimault *et al*. (2009b), ce qui tendrait à indiquer une possible implication de cette région, indistinctement de la modalité, en STM pendant la période de rétention.