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Processing load impairs coordinate integration for the localization of touch

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Abstract To perform an action toward a touch, the tactile spatial representation must be transformed from a skin-based, anatomical reference frame into an external reference frame. Evidence suggests that, after transformation, both anatomical and external coordinates are integrated for the location estimate. The present study investigated whether the calculation and integration of external coordinates are automatic processes. Participants made temporal order judgments (TOJs) of two tactile stimuli, one applied to each hand, in crossed and uncrossed postures. The influence of the external coordinates of touch was indicated by the performance difference between crossed and uncrossed postures, referred to as the *crossing effect*. To assess automaticity, the TOJ task was combined with a working memory task that varied in difficulty (size of the working memory set) and quality (verbal vs. spatial). In two studies, the crossing effect was consistently reduced under processing load. When the load level was adaptively adjusted to individual performance (Study 2), the crossing effect additionally varied as a function of the difficulty of the secondary task. These modulatory effects of processing load on the crossing effect were independent of the type of working memory. The sensitivity of the crossing effect to processing load suggests that coordinate integration for touch localization is not fully automatic. To reconcile the present results with previous findings, we suggest that the genuine remapping process—that is, the transformation of anatomical into external coordinates—proceeds automatically, whereas their integration in service of a combined location estimate is subject to top-down control.

Keywords Spatial localization · Automaticity · Touch

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Introduction

When we are touched, the location of the tactile stimulus is initially represented in a skin-based, anatomical reference frame (Disbrow et al. 2000; Penfield & Boldrey, 1937; Yang, 1993). However, to integrate information from different senses and to perform an action on the tactile stimulus, tactile stimuli have to be coded in an external-spatial reference frame (Pouget, Ducom, Torri, & Bavelier, 2002; Sober & Sabes, 2005). This coordinate transformation of somatosensory, visual, and proprioceptive information into external tactile coordinates has been termed *remapping of touch* (Driver & Spence, 1998).

The existence of the external coordinates of touch can be demonstrated experimentally when temporal order judgments (TOJs) of two tactile stimuli, one applied to each hand, are performed with crossed rather than uncrossed hands: TOJ performance is remarkably reduced in crossed, as compared with uncrossed, postures (Shore, Spry, & Spence, 2002; Yamamoto & Kitazawa, 2001). This crossing effect has been interpreted as an indicator of the influence of the external reference frame, because, in the crossed posture, the anatomical and external coordinates of left and right are in conflict, whereas they coincide in the uncrossed posture. However, it would be possible to perform the TOJ task based on anatomical coordinates alone, that is, posture could be entirely ignored to solve the task. Therefore, the crossing effect has been interpreted as indicating that tactile remapping is automatic (Azañón, Camacho, & Soto-Faraco 2010a; Kitazawa, 2002; Röder, Rösler, & Spence, 2004). However, it has never been examined whether tactile localization indeed fulfills the criteria of an automatic process.

The fact that tactile stimuli are remapped does not necessarily imply that the anatomical spatial representation is abolished. On the contrary, tactile stimuli appear to be encoded in both anatomical and external reference frames at the same time (Buchholz, Jensen, & Medendorp, 2011, 2013; Heed & Röder, 2010).

Recent results from computational modeling have suggested that tactile localization comprises at least two specifiable processing steps. The first step is the genuine spatial remapping process—that is, the transformation from skin-based, anatomical into external coordinates. The second step is the combination of these two pieces of information into an integrated location estimate (Badde, Heed, & Röder, 2013). However, previous studies have usually not explicitly differentiated between the two processes involved in touch localization. Accordingly, experimental findings have been attributed to the transformation process (e.g., Azañón et al. 2010a, b; Azañón & Soto-Faraco, 2007; Röder, Spence, & Rösler, 2002; Wada, Yamamoto, & Kitazawa, 2004), possibly because of the assumption that TOJ responses are made on the external coordinates of touch alone (Kitazawa, 2002; Yamamoto & Kitazawa, 2001). Here, we addressed the potential automaticity of both processes, remapping and coordinate integration.

Automatic processes are defined as not requiring attention and as being executed effortlessly without conscious control (Posner & Snyder, 1975; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Automaticity of cognitive processes is often tested by systematically manipulating processing load (Moors & De Houwer, 2006). For example, processes are usually considered to be automatic if they are insensitive to working memory (WM) manipulations (Logan, 1979).

Only few studies have used load manipulations to assess automaticity in multisensory integration (for an overview of the role of attention, see Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Some studies did not find an influence of WM load on integrative processes and, consequently, concluded that multisensory integration is an automatic process. For example, neither the level of WM load nor the demands on visual-spatial attention were found to modulate the influence of cross-modal spatial congruency on activity in the visual cortex in a spatial tactile–visual integration paradigm (Zimmer & Macaluso, 2007). Additionally, Baart and Vroomen (2010) did not find any effect of the level of concurrent verbal and visual-spatial WM load on the influence of lipreading on phoneme perception. In contrast, audio-visual integration of speech signals, as measured by the McGurk illusion, has been observed to be sensitive to visual, auditory, and tactile attentional load (Alsius, Navarra, Campbell, & Soto-Faraco, 2005; Alsius, Navarra, & Soto-Faraco, 2007): Significantly fewer instances of visual–auditory fusion were observed when a WM task was performed during speech observation, as compared with single-task conditions. In these studies the influence of load was independent of the modality of the information held in WM. Furthermore, these top-down modulations did not mirror attentional influences on unisensory processing, since performance in unisensory conditions remained unchanged by the introduction of a concurrent WM task (Alsius et al., 2005).

Here, we used load manipulations to investigate whether the processes involved in touch localization—that is, remapping and coordinate integration—are automatic or top-down controlled. More specifically, we tested the influence of processing load on the TOJ crossing effect by combining the tactile TOJ task with WM tasks of varying difficulty and quality. Two different aspects of processing load were manipulated: dual-task coordination and WM load (see Lavie, Hirst, de Fockert, & Viding, 2004). Any modulation of the TOJ crossing effect as a function of processing load would argue against a full automaticity of the associated processes.

We expected that increased processing load would impair processes that depend on top-down control (Lavie et al., 2004). If the genuine remapping process is influenced by the load manipulation, we would expect a reduced influence of the external coordinates on TOJ, since external coordinates are the result of remapping. If the integration of the anatomical and external coordinates is influenced by the load manipulation, we would expect a reduced influence of both external and anatomical coordinates. A reduced influence of the anatomical coordinates should result in impaired TOJ performance in both posture conditions, since the anatomical coordinates do not change with hand crossing and, thus, should not modulate the size of the crossing effect. In contrast, a reduced influence of the external coordinates would have opposite effects in uncrossed and crossed conditions and, therefore, modulate the size of the crossing effect. In uncrossed conditions, the external coordinates point toward the same response as the anatomical coordinates; that is, they provide concordant information. Integrating them, therefore, improves TOJ performance (Röder, Pagel, & Heed, 2013), and, in turn, reducing their influence impairs TOJ performance. In contrast, in the crossed posture condition, the external coordinates provide spatial information incongruent to the anatomical reference frame; thus, they hamper, rather than support, performance in the anatomically coded TOJ task. Hence, reducing the influence of the external coordinates should result in improved TOJ performance in the crossed conditions. In sum, effects of processing load on the processes of genuine remapping and coordinate integration would result in a smaller TOJ crossing effect.

To differentiate between these processes, we additionally varied the quality of WM load. It is known that the remapping of touch is closely associated with the visual modality. For example, congenitally blind adults do not exhibit crossing effects (Röder, Föcker, Hötting, & Spence, 2008; Röder et al., 2004), and vision of crossed rubber hands affects TOJ performance (Azañón & Soto-Faraco, 2007). Accordingly, we hypothesized that the genuine remapping process might be less efficient under conditions of high visual-spatial WM load, leading to a reduction of the TOJ crossing effect. However, a verbal WM task should not affect remapping and, thus, should not modulate the TOJ crossing effect. In contrast, the integration of the anatomical and external coordinates is assumed to be independent of the integrated content. Thus, top-down influences on coordinate integration should not depend on the type of the secondary task.

Study 1: Tactile localization under processing load

In the first study, we tested the influence of the *n*-back task, a well-established WM task (e.g., Kane, Conway, Miura, & Colflesh, 2007; Owen, McMillan, Laird, & Bullmore, 2005) on the TOJ crossing effect. Participants performed a tactile TOJ task either as a single task or in trial-by-trial alternation with the *n*-back task. Moreover, the difficulty (load) and the quality of WM (spatial vs. verbal) were varied. For the latter, spatial and verbal items had to be remembered across trials.

General processing load effects on the crossing effect were assessed by comparing the TOJ performance in the no-load (single task), the low-load, and the high-load conditions. WM type specific effects were tested by comparing performance between no-load, verbal load, and spatial load conditions.

Method

Participants

Seventeen right-handed students (6 male, 18–37 years of age, mean = 25 years) from the University of Hamburg took part in all experiments. Originally, 56 participants volunteered for the study: 39 participants (70 %) performed below the recruitment criterion of 65 % accuracy in the crossed hand condition in a screening experiment and were not invited to participate in the study reported here. A priori power analysis with G*Power (Faul, Erdfelder, Buchner, & Lang, 2009; Faul et al. 2007) recommended a sample size of 18 participants when testing for a small effect of .25 with an alpha of .05 and a beta of .05. All participants reported normal or corrected-to-normal vision and being free of tactile impairments. In return for their attendance, they received course credit or were compensated with 7 Euro/h. The experiment was conducted in accordance with the guidelines of the Declaration of Helsinki (World Medical Association, 2008).

Apparatus and stimuli

Participants sat at a table, resting their hands and elbows on the table surface. The index fingers and the right foot were placed on response devices. The arms were either crossed or uncrossed. A foam cushion was placed underneath the upper arm to avoid skin contact between the hands and arms in the crossed condition.

The manual response devices were small plastic cubes (height, 1.5 cm; width, 2.5 cm; length, 4 cm) with a concave indentation of the size of a single phalanx (diameter, 2 cm), in which the finger tip rested. A light barrier detected when the finger was lifted from its resting position, and this was recorded as a response. The distance between the response devices was kept at 25 cm throughout the experiments. Foot responses were given by lifting either the toes or the heel of the right foot, which was placed in a custom-made foot pedal.

Tactile stimulators (Oticon bone conductors, type BC 461–012, Oticon Ltd., Milton Keynes, U.K., sized about 1.6 × 1 × 0.8 cm) were taped to the middle fingers, covering the whole fingernail and some proximate skin. For stimulation, they were driven with a frequency of 200 Hz (i.e., a square wave with cycle duration of 5 ms, including on and off phases) for 15 ms.

To shield off any auditory cues produced by the tactile stimulators, participants wore ear plugs, as well as headphones playing white noise.

Visual stimuli were displayed on a 19-in. LCD monitor with a refresh rate of 60 Hz, placed 75 cm in front of the participants. Stimuli consisted of single digits, ranging from 1 to 9, shown at one of nine positions arranged in a centrally positioned 3 × 3 array. Each field of the array had a length and width of 16 mm (1.22° of visual angle). Digits were, on average, 9 mm high (0.46° of visual angle) and 6 mm wide (0.69° of visual angle). Stimuli were presented for 500 ms. A fixation cross was shown at the center of the screen, whenever no visual stimulus was presented. Digits, fixation cross, and instructions were displayed in white color on a black background.

The experiment was controlled by the software Presentation, version 14.5 (Neurobehavioral Systems, Albany, CA), which interfaced with custom-built hardware to drive stimulators and record responses.

Tasks

TOJ task On each trial, two tactile stimuli, one to each middle finger, were presented in succession. Participants were asked to indicate the stimuli's temporal order by lifting the index finger of the hand to which the first stimulus had been applied. Responses had to be withheld until the second stimulus had been presented. No feedback was provided during the experiment.

n-back task A series of single digits was presented at varying locations on the screen. Participants were asked to remember either the identity of the digit (verbal task) or its position (spatial task). In the low WM load conditions, each stimulus was compared with the preceding stimulus (n = 1). In the high WM load conditions, stimuli were compared with the stimulus before the preceding stimulus (n = 2). Responses were given with the right foot; response assignment (heel and toes) was counterbalanced across participants.

Design

The study consisted of four experiments: In Experiments 1.1 and 1.2, the TOJ task and the *n*-back task were administered as single tasks, respectively. In Experiments 1.3 and 1.4, both tasks were combined into a dual-task experiment. Experiment 1.3 comprised the TOJ task and the verbal variant of the *n*-back task, whereas Experiment 1.4 combined the TOJ task and the spatial *n*-back task.

Two within-participants factors reflect manipulations of the *n*-back task (see Fig. 1): the number of stimuli to be memorized (factor, load level; levels: no load [Experiment 1.1], low load [$n = 1$], and high load [$n = 2$]) and the relevant stimulus attribute (factor, WM type; levels: no load [Experiment 1.1], verbal load [digit task], and spatial load [position task]). Experiments 1.1, 1.3, and 1.4 represent distinct levels of the WM type factor (Experiment 1.1, no load; Experiment 1.3, verbal load; and Experiment 1.4, spatial load).

Experiments 1.1, 1.3 and 1.4 involved the TOJ task and manipulated three additional within-participants factors: hand posture (factor, crossing status; levels: uncrossed or crossed), the hand stimulated first (factor, stimulus hand; levels: left or right hand), and the time interval between the two tactile stimuli (factor, stimulus onset asynchrony [SOA]; levels: 50, 80, 110, 150, 200, 250, or 300 ms).

Procedure

TOJ: Single task (Experiment 1.1) Trials were 3,000 ms long. The time interval between trials (ITI) varied randomly from 500 to 800 ms. The experiment was divided into four blocks of 50 trials each, and the experiment took approximately 30 min. The hand and SOA factors were varied within blocks, whereas crossing status changed every two blocks.

n-back: Single task (Experiment 1.2) Each trial was 4,000 ms long. The experiment was divided into halves of four blocks each, in which either the verbal or the spatial *n*-back task was administered. Each block consisted of 30 trials which were grouped into three sequences of 10 trials each. The experiment took approximately 60 min. The load level factor changed every other block.

Dual tasks (Experiments 1.3 and 1.4) Both tasks, TOJ and *n*-back, were interleaved (see Fig. 2, left panel). At the beginning of each trial, an *n*-back stimulus was presented, and participants were required to respond immediately to this stimulus. For the first *n*-back stimulus (one-back condition), and for the first two *n*-back stimuli (two-back condition), respectively participants had to respond as in the mismatch trials. The first tactile stimulus was applied 1,500 ms after the offset of the *n*-back stimulus. The second touch followed after the variable SOA. To keep the retention interval of the *n*-back stimuli constant, every dual-task trial ended 2,000 ms after the application of the first touch. Each dual-task experiment (Experiments 1.3 and 1.4) was divided into 16 blocks consisting of 50 trials, which were grouped into five sequences of 10 trials each. One dual-task experiment took 120 min. The hand and SOA factors were varied within blocks, whereas crossing status changed every 8 blocks and load level every 4th block.

General procedure Participants performed Experiments 1.1 and 1.2 during a single experimental session. The order of experiments and conditions was counterbalanced across participants. After finishing the experiments, participants were asked whether

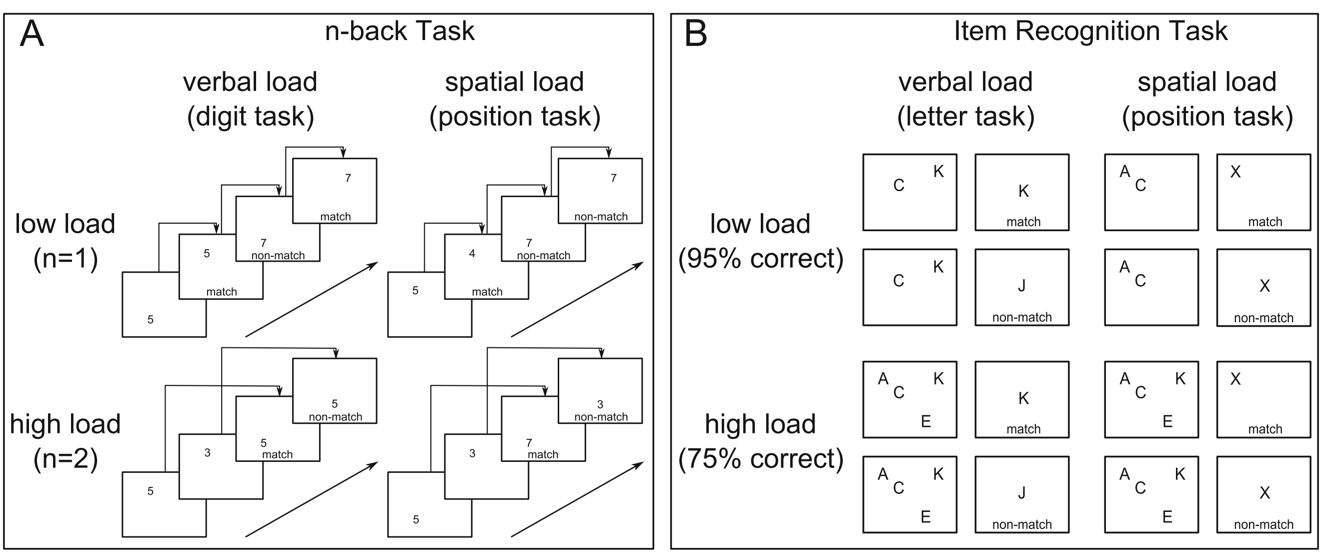

Fig. 1 Schematic illustration of the working memory (WM) task conditions in Study 1 (**a**) and Study 2 (**b**). Both tasks varied with respect to the amount of load (load level) and the relevant stimulus attributes (WM type)

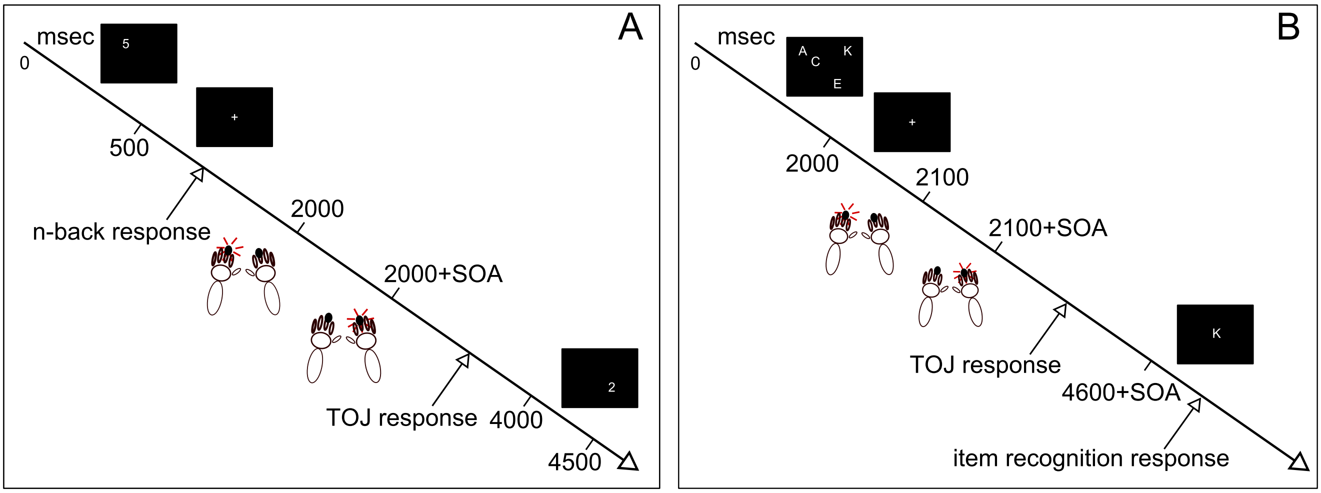

Fig. 2 Schematic illustration of dual-task experimental trials in Study 1 (**a**) and Study 2 (**b**). Both studies combined a working memory task with tactile temporal order judgments (TOJ). In Study 1, TOJ and the *n*-back task were combined. In Study 2, an item recognition task (Sternberg task) and the same TOJ task as in Study 1 were combined

they had employed specific strategies to solve the tasks or whether they had encountered any difficulties in the experiments.

Data analysis

In Experiments 1.1, 1.3, and 1.4, trials with TOJ reaction times (RTs) shorter than 150 ms and longer than 1,500 ms were excluded from further analysis (1.1 % of all trials). For Experiment 1.2, trials with *n*-back responses shorter than 150 ms and longer than 2,000 ms were excluded (9.3 % of all trials). In the dual-task experiments, Experiments 1.3 and 1.4, trials lacking a response in one of the tasks were excluded (1.8 % of all trials).

Analyses of TOJ data TOJ performance was quantified in two different ways: First, mean accuracies and RTs were analyzed. Second, a probit analysis of the data was conducted. To this aim, responses were transformed into *right hand first* responses, indicating whether or not participants judged the anatomically right hand to be stimulated first (e.g., Shore et al., 2002; Yamamoto & Kitazawa, 2001). Then, probit values of the proportion of right hand first responses were calculated for each SOA by applying the inverse normal distribution $X \sim N(0, 1)$ ($\text{probit}(p_{\text{right hand first}}) = z \Leftrightarrow \Phi(z) = p_{\text{right hand first}}$). The resulting probits were linearly regressed onto SOA values ranging from −110 to 110 ms (with negative SOA indicating *left hand first*-stimuli). The slope of the resulting regression line was used as a measure of performance, with steeper probit slopes indicating better performance.

Three repeated measures ANOVAs using type III sum of squares were performed on each dependent variable. First, to test for general influences of processing load on the crossing effect, an ANOVA with crossing status and load level (no load, low load, high load) as factors was conducted. Second, an ANOVA with crossing status and WM type (verbal vs. spatial) as factors was performed to investigate working memory type specific influences. Finally, to test for interactions between the influences of the load level and WM type factors, an ANOVA with these factors, as well as the crossing status factor, was conducted on the data from Experiments 1.3 and 1.4. Due to the nested design, Experiment 1.1 was not included in the third analysis. To further explore significant interactions, pairwise paired *t*-tests were calculated on difference scores (uncrossed − crossed) representing the crossing effect (see Maxwell & Delaney, 2004, on the advantages of this approach over contrast analyses). The resulting *p*-values were corrected for multiple comparisons, following a procedure suggested by Holm (1979).

Analyses of n-back data Repeated measures ANOVAs with load level and WM type as factors were conducted on accuracy and on RT data from the n-back task. Due to the nested design, separate analyses were conducted for data from single-task (Experiment 1.1) and dual-task (Experiments 1.3 and 1.4) experiments. Only significant results are reported (type I error level of 5 % unless noted otherwise).

Results

Analyses of TOJ data

Analysis 1: Overall influence of processing load on tactile localization For the TOJ task, repeated measures ANOVAs with crossing status and load level as factors revealed a significant main effect of crossing status [probit slope, $F(1, 16) = 61.51$, $p < .001$, $\eta_g^2 = .38$; accuracy, $F(1, 16) = 39.86$, $p < .001$, $\eta_g^2 = .43$; RT, $F(1, 16) = 34.97$, $p < .001$, $\eta_g^2 = .23$], a significant main effect of load level [probit slope,

$F(1.65, 26.40) = 11.86$, $p < .001$, $\eta_g^2 = .07$; RT, $F(1.27, 20.35) = 5.37$, $p = .024$, $\eta_g^2 = .05$], and a significant interaction between these factors [probit slope, $F(1.88, 30.08) = 25.20$, $p < .001$, $\eta_g^2 = .09$; RT, $F(1.46, 23.36) = 22{,}56$, $p < .001$, $\eta_g^2 = .05$]. Performance was impaired in the crossed, as compared with the uncrossed, posture (Fig. 3). This crossing effect was reduced in the dual task (i.e., under low and high load in Experiments 1.3 and 1.4), as compared with the single-task condition (i.e., as compared with the no load in Experiment 1.1) [no load vs. low load: probit slope, $t(16) = 5.86$, $p < .001$, $r = .83$; RT, $t(16) = 4.34$, $p < .001$, $r = .74$; no load vs. high load: probit slope, $t(16) = 7.01$, $p < .001$, $r = .87$; RT, $t(16) = 6.46$, $p = .001$, $r = .85$]. We did not observe a significant difference in the size of the crossing effect between low- and high-load conditions (low load vs. high load: probit slope, $r = .28$; RT, $r = .22$).

Analysis 2: Influences of working memory type on tactile localization Repeated measures ANOVAs on the TOJ data with crossing status and WM type as factors revealed a significant main effect of crossing status [probit slope, $F(1, 16) = 69.55$, $p < .001$, $\eta_g^2 = .39$; accuracy, $F(1, 16) = 39.81$, $p < .001$, $\eta_g^2 = .43$; RT, $F(1, 16) = 34.84$, $p < .001$, $\eta_g^2 = .23$], a significant main effect of WM type [probit slope, $F(1.89, 30.21) = 7.60$, $p = .002$, $\eta_g^2 = .06$; RT, $F(1.66, 26.56) = 4.24$, $p = .031$, $\eta_g^2 = .04$], and a significant interaction between these factors [probit slope, $F(1.64, 26.24) = 24.81$, $p < .001$, $\eta_g^2 = .08$; RT, $F(1.49, 23.87) = 23.42$, $p < .001$, $\eta_g^2 = .04$]. The crossing effect was reduced in dual-task (i.e., under verbal and spatial load, Experiment 1.3 and Experiment 1.4, respectively), as compared with single-task (i.e., Experiment 1.1) conditions [no load vs. verbal load: probit slope, $t(16) = 5.07$, $p < .001$, $r = .78$; RT, $t(16) = 5.74$, $p < .001$, $r = .82$; no load vs. spatial load: probit slope, $t(16) = 8.96$, $p < .001$, $r = .91$; RT, $t(16) = 4.84$, $p < .001$, $r = .77$] (Fig. 3). Importantly, the size of the crossing effect did not significantly differ between the verbal and the spatial load conditions (verbal load vs. spatial load: probit slope, $r = .21$; RT, $r = .08$).

Analysis 3: Interactions between influences of load level and WM type on tactile localization A repeated measures ANOVA with crossing status, load level, and WM type as factors was conducted on TOJ data from the dual-task experiments (Experiments 1.3 and 1.4). This analysis confirmed a significant main effect of crossing status [probit slope, $F(1, 16) = 36.07$, $p < .001$, $\eta_g^2 = .24$; accuracy, $F(1, 16) = 26.48$, $p < .001$, $\eta_g^2 = .38$; RT, $F(1, 16) = 18.34$, $p < .001$, $\eta_g^2 = .12$] and revealed a significant interaction between all three factors [RT: $F(1, 16) = 6.94$, $p = .018$, $\eta_g^2 < .01$] (Table 1). Post hoc conducted pairwise t-tests revealed significant differences only for comparisons between uncrossed performance in one condition and crossed performance in another condition (Table 2). To confirm this result, we conducted pairwise t-tests on the crossing status difference score (uncrossed −

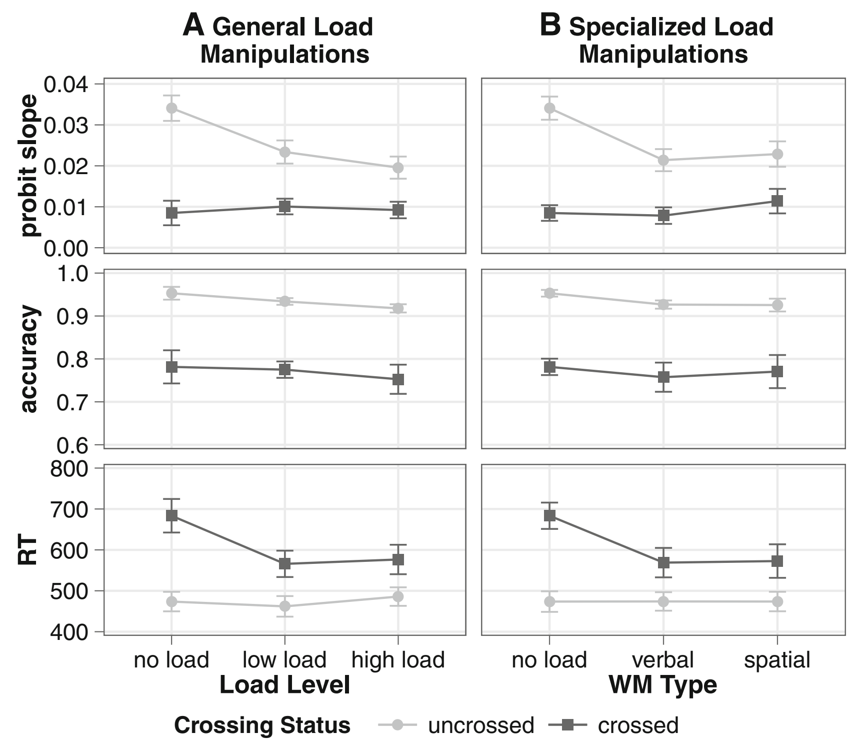

Fig. 3 Mean slopes, accuracies and reaction times (RTs) for temporal order judgment (TOJ) performance in Study 1: TOJ performance is viewed from two perspectives: processing load level (**a**) and working memory type (**b**). All measures are shown separately for crossed (light gray) and uncrossed (dark gray) posture conditions. Error bars show standard errors

Table 1 Temporal order judgment performance in the dual-task experiments of Study 1 (Experiments 1.3 and 1.4)

Crossing Status	Load Level	WM Type	Slope	Accuracy	RT
Uncrossed	low load	verbal	0.0287 (0.0036)	0.94 (0.01)	458.10 (23.09)
Crossed	low load	verbal	0.0099 (0.0030)	0.76 (0.03)	575.32 (36.61)
Uncrossed	high load	verbal	0.0235 (0.0030)	0.92 (0.01)	491.06 (25.32)
Crossed	high load	verbal	0.0091 (0.0026)	0.75 (0.04)	567.74 (40.71)
Uncrossed	low load	spatial	0.0283 (0.0031)	0.93 (0.01)	467.00 (23.14)
Crossed	low load	spatial	0.0157 (0.0034)	0.79 (0.04)	557.34 (39.55)
Uncrossed	high load	spatial	0.0265 (0.0039)	0.92 (0.02)	480.78 (27.03)
Crossed	high load	spatial	0.0130 (0.0040)	0.75 (0.04)	588.70 (44.49)

Note. Mean values and standard errors (in parentheses) are reported

crossed), which did not show any significant change of the crossing effect between any pair of the four combinations of load level and WM type after correcting for multiple comparisons.

Analyses of n-back data

Performance in the single-task experiment: Experiment 1.2 Repeated measures ANOVAs with load level and WM type factors showed a significant main effect of load level [accuracy, $F(1, 16) = 6.32$, $p = .023$, $\eta_g^2 = .03$; RT, $F(1, 16) = 20.58$, $p < .001$, $\eta_g^2 = .07$]. Responses were slower and less accurate in high-load than in low-load conditions (Table 3).

Performance in the dual-task experiments: Experiments 1.3 and 1.4 Repeated measures ANOVAs with crossing status, load level, and WM type as factors revealed a significant main effect of load level for accuracy, $F(1, 16) = 14.25$, $p = .002$, $\eta_g^2 = .47$, and for RT, $F(1, 16) = 7.36$, $p = .015$, $\eta_g^2 = .06$. Responses were slower and less accurate in high-load conditions than in low-load conditions (Table 3).

Discussion

The aim of the present study was to investigate whether tactile remapping and coordinate integration for tactile localization are automatic processes. We tested whether a marker of the influence of the external coordinates of touch, the crossing effect in a tactile TOJ task, was modulated by the level and quality of processing load. To this end, tactile TOJs in crossed and uncrossed postures were combined with a verbal and a spatial *n*-back task of two different difficulty levels. The TOJ crossing effect (that is, the difference in performance between crossed and uncrossed hand postures) was smaller under concurrent processing load than under no-load conditions—that is, in a single-task condition. This effect was due to a

Table 2 Results of the post hoc analysis of temporal order judgment performance in the dual-task conditions (Study 1, RT)

	Low Load Spatial Crossed	High Load Verbal Crossed	Low Load Spatial Crossed	High Load Spatial Crossed	Low Load Verbal Uncrossed	High Load Verbal Uncrossed	Low Load Spatial Uncrossed
High load verbal crossed	$t(16)=0.34$ $p=1.000$						
Low load spatial crossed	$t(16)=0.76$ $p=1.000$	$t(16)=0.48$ $p=1.000$					
High load spatial crossed	$t(16)=0.50$ $p=1.000$	$t(16)=0.74$ $p=1.000$	$t(16)=1.66$ $p=1.000$				
Low load verbal uncrossed	$t(16)=4.65$ $\mathbf{p=.007}$	$t(16)=3.53$ $p=.061$	$t(16)=2.72$ $p=.225$	$t(16)=3.27$ $p=.085$			
High load verbal uncrossed	$t(16)=3.08$ $p=.115$	$t(16)=3.42$ $p=.073$	$t(16)=2.11$ $p=.662$	$t(16)=2.57$ $p=.286$	$t(16)=1.96$ $p=.807$		
Low load spatial uncrossed	$t(16)=4.46$ $\mathbf{p=.011}$	$t(16)=3.68$ $\mathbf{p=.048}$	$t(16)=3.28$ $p=.085$	$t(16)=3.64$ $p=.051$	$t(16)=0.53$ $p=1.000$	$t(16)=1.25$ $p=1.000$	
High load spatial uncrossed	$t(16)=4.01$ $\mathbf{p=.025}$	$t(16)=3.37$ $p=.074$	$t(16)=3.41$ $p=.073$	$t(16)=4.06$ $\mathbf{p=.024}$	$t(16)=1.02$ $p=1.000$	$t(16)=0.54$ $p=1.000$	$t(16)=0.84$ $p=1.000$

Note. *p*-values have been corrected for multiple comparisons, following Holm (1979)

Table 3 Mean values and standard errors in the *n*-back task (Study 1)

Load Level	WM Type	Crossing Status	Accuracy	RT
Single-task condition (Experiment 1.2)				
Low load	verbal		0.95 (0.02)	1,084.53 (50.39)
High load	verbal		0.93 (0.02)	1,200.41 (45.43)
Low load	spatial		0.96 (0.02)	1,107.22 (45.00)
High load	spatial		0.93 (0.02)	1,205.18 (54.98)
Dual-task condition (Experiments 1.3 & 1.4)				
Low load	verbal	uncrossed	0.89 (0.03)	1,353.33 (162.73)
High load	verbal	uncrossed	0.84 (0.03)	1,439.97 (158.79)
Low load	verbal	crossed	0.89 (0.02)	1,361.20 (168.78)
High load	verbal	crossed	0.84 (0.03)	1,447.79 (158.58)
Low load	spatial	uncrossed	0.90 (0.02)	1,377.15 (177.40)
High load	spatial	uncrossed	0.89 (0.02)	1,461.51 (167.19)
Low load	spatial	crossed	0.93 (0.01)	1,339.82 (173.37)
High load	spatial	crossed	0.87 (0.02)	1,479.97 (170.73)

Note. Standard errors are shown in parentheses

decrease in performance with uncrossed hands, but also to constant or improved performance with crossed hands in the dual-task, as compared with the single-task conditions. In contrast, the size of the crossing effect depended neither on the difficulty level nor on the WM type of the *n*-back task.

The present results contradict the suggestion that tactile localization in external space is a fully automatic process (Azañón et al. 2010a; Kitazawa, 2002; Röder et al., 2004). Rather, they indicate that localizing touch involves some processing steps under top-down control. In accordance with the suggestion that touch localization in the TOJ task is based on anatomical and on external coordinates, the crossing effect was reduced, rather than amplified, under processing load. Recall that the external coordinates support TOJ performance in the uncrossed conditions but are in conflict in the crossed conditions. Consequently, the observed reduction of the crossing effect can be associated with a decrease in the influence of the external coordinates.

We hypothesize that the difference between the low- and high-load conditions might have been too small to result in statistically significant different modulations of the crossing effect (see, e.g., Regenbogen et al., 2012). It is important to note that single- and dual-task conditions differ not only in working memory load, but additionally in control processes such as task coordination (Brand-D'Abrescia & Lavie, 2008; Lavie et al., 2004). Thus, we are not able to exclude that tactile localization interacted only with top-down processes, which are distinct from WM.

Furthermore, we did not observe a difference of the type of WM (verbal vs. spatial). This result suggests that processing load impaired the integration of the anatomical and external coordinates, rather than the genuine remapping process, which we assume not to interact with a verbal task. However, it is known that there is a link between the representation of numbers and the representation of space (e.g., Fischer, Castel, Dodd, & Pratt, 2003). It is, therefore, possible that the digit task had a spatial component that influenced the crossing effect in a similar manner as in the spatial WM task.

Notably, some participants reported having used a nonspatial strategy in the spatial high-load conditions. They verbalized digit positions—for example, by using verbal labels such as "lower left corner" or "middle position upper row"—rather than holding the position in spatial WM. Because of its verbal character, this strategy may have also reduced the processing difference between verbal and spatial load conditions.

Study 2: Tactile localization under adaptive processing load

This study was designed to overcome the three potential confounds of Study 1. First, the amount of load was adapted to participants' individual WM task performance levels. Instead of the *n*-back task, we employed an item recognition task known as the *Sternberg task* (Sternberg, 1966). This task allows for a continuous adaptation of the number of items to be remembered, thus allowing precise control of each participant's individual performance at specified levels of WM difficulty. The level of processing load was adapted independently for the verbal and spatial load conditions, allowing us to balance difficulty across the two types of WM (verbal and spatial). Second, we substituted numbers by letters as memory items, to eliminate the confound of a link between verbal and spatial materials. Third, the number of possible item positions was increased from 9 to 25, to discourage verbalizing strategies in the spatial WM task. Finally, no performance-based criteria were applied in participant recruitment (in Study 1, volunteers were tested only if they reached 65 % TOJ accuracy with crossed hands), to ease participant recruitment and to avoid a lack of generalizability due to a highly selective sample.

Method

Participants

Seventeen right-handed students (7 male, 20–35 years of age, mean = 25 years) from the University of Hamburg participated in the study. All reported normal or corrected-to-normal vision and no tactile impairments. Participants received course credit or were compensated with 7 Euro/h. Three additional participants did not finish the experiment, one because of technical problems, one fainted, and one fell asleep during the experiment. The experiment was conducted in accordance with the guidelines of the Declaration of Helsinki (World Medical Association, 2008).

Apparatus and stimuli

The apparatus and tactile stimuli were identical to the ones in Study 1. The item recognition task comprised two visual stimulus displays, a prime and a probe stimulus. Prime stimuli consisted of a variable number of different letters from the Latin alphabet (excluding X). Each letter was displayed at one of 25 positions, arranged in a centrally placed 5 × 5 array. Each field of the array had a length and width of 18 mm (1.38° of visual angle). The letters were, on average, 7 mm high (0.53° of visual angle) and 5 mm wide (0.38° of visual angle). Probe stimuli contained only one letter. In the verbal item recognition task, a probe letter ranging from A to Z (excluding X) was displayed at the central position. In contrast, in the spatial item recognition task, the letter X was presented as a spatial probe at any one of the other 24 possible positions.

Tasks

TOJ task The TOJ task was identical to the TOJ task in Study 1.

Item recognition task We used an adaptive variant of the item recognition task (Sternberg, 1966). Participants memorized either the identities of the letters (verbal task) presented in the prime display or their positions (spatial task). After a retention interval, participants were asked to indicate whether or not the presented probe stimulus was part of the memory set. Responses were given with the right foot. Response assignment (heel and toes) was counterbalanced across participants.

Design

The study consisted of four experiments: In Experiment 2.1, the TOJ task and, in Experiment 2.2, the item recognition task were performed as single tasks. In Experiment 2.3, the TOJ task and the verbal item recognition task and, in Experiment 2.4, the TOJ task and the spatial item recognition task were combined into a dual task.

Two factors were manipulated with respect to the item recognition task (Fig. 1): the amount of processing load (factor, load level; levels: no load [Experiment 2.1], low load, or high load) and the type of load (factor, WM type; levels: no load [Experiment 2.1], verbal load [Experiment 2.2], or spatial load [Experiment 2.3]). To control task difficulty across participants and throughout the experiment, the number of simultaneously presented letters was continuously adapted to the individual participant's performance, using a fast converging adaptive procedure, named *accelerated stochastic approximation* (Kesten, 1958; Robbins & Monro, 1951). This algorithm adapted the number of displayed stimuli when the proportion of correct responses diverged from 75 % correct responses for the high-load condition and from 95 % correct responses for the low-load condition:

$$x(n+1) = x(n) - \frac{C}{n_{\text{shifts}}}(z(n) - \phi), \qquad (1)$$

with x = number of items, n = number of trials, C = initial step size, $z(n) \in \{0,1\}$ = response in trial n, ϕ = target probability, n_{shifts} = number of response direction shifts.

Three additional within-participants factors reflect variations in the TOJ task: hand posture (factor, crossing status; levels: uncrossed or crossed), the hand stimulated first (factor, stimulus hand; levels: left or right hand), and the time interval between the two tactile stimuli (factor, SOA; levels: 50, 80, 110, or 300 ms).

Procedure

TOJ: Single task (Experiment 2.1) The procedure of the TOJ task was identical to the TOJ task in Study 1.

Item recognition: Single task (Experiment 2.2) First, the prime stimulus was presented for 2,000 ms. After a retention interval of 1,000 ms the probe stimulus was displayed for 500 ms. Trials were separated by a constant ITI of 100 ms. The experiment consistent of two parts, administering either the verbal or the spatial item recognition task. Each part consisted of eight blocks of 20 trials each. The experiment took approximately 50 min. The load level factor changed every other block.

Dual tasks (Experiments 2.3 and 2.4) In these experiments, each TOJ trial was embedded between the prime and probe display of an item recognition trial (see Fig. 2, right panel). At the beginning of each trial, the visual WM stimulus array was presented for 2,000 ms. The first tactile stimulus was applied 100 ms after the offset of the visual stimulus array. Participants made a TOJ response as soon as possible after the onset of the second tactile stimulus. Then, 2,500 ms after the onset of the second tactile stimulus, the visual probe stimulus was presented for 500 ms. The time for responding to the WM probe was not limited. Each dual-task experiment was divided into eight blocks of 48 trials and took 90 min. The stimulus hand and SOA factors were varied within blocks, whereas crossing status changed every two blocks and load level every fourth block.

General procedure Participants performed Experiments 2.1 and 2.2 during a single experimental session. The order of experiments and condition order were counterbalanced across participants.

Data analysis

Analyses of TOJ data Trials with TOJ RTs shorter than 150 ms and longer than 2,000 ms were excluded from further analysis of TOJ performance (2.7 % of all trials). The upper TOJ RT criterion was raised, in comparison to Study 1 (cutoff at 1,500 ms), because overall RTs were longer in this study. All other statistical procedures were the same as in Study 1.

Analyses of item recognition data Trials with item recognition RTs shorter than 150 ms and longer than 3,000 ms were excluded from the analysis of item recognition data (5.2 % of all trials). All other statistical procedures were the same as in Study 1.

Results

Analyses of TOJ data

Analysis 1: Overall influence of processing load on tactile localization Analysis of TOJ data with repeated measures ANOVAs with crossing status and load level as factors revealed a significant main effect of crossing status [probit slope, $F(1, 16) = 77.48$, $p < .001$, $\eta_g^2 = .53$; accuracy, $F(1, 16) = 73.35$, $p < .001$, $\eta_g^2 = .60$; RT, $F(1, 16) = 53.53$, $p < .001$, $\eta_g^2 = .11$], a significant main effect of load level [probit slope, $F(1.66, 26.51) = 25.29$, $p < .001$, $\eta_g^2 = .21$; accuracy, $F(1.53, 24.51) = 5.51$, $p = .016$, $\eta_g^2 = .03$; RT, $F(1.20, 19.13) = 14.62$, $p < .001$, $\eta_g^2 = .13$], and a significant interaction between these factors [probit slope, $F(1.45, 23.17) = 24.54$, $p < .001$, $\eta_g^2 = .23$; accuracy, $F(1.50, 24.06) = 11.00$, $p < .001$, $\eta_g^2 = .06$; RT, $F(1.37, 21.93) = 7.25$, $p = .008$, $\eta_g^2 = 0.01$]. Post hoc analyses confirmed that the crossing effect was reduced in the dual-task condition (i.e., under low and high load), as compared with the single-task (i.e., no-load) condition (no load vs. low load: probit slope, $t(16) = 4.71$, $p < .001$, $r = .76$; accuracy, $t(16) = 2.77$, $p = .027$, $r = .57$; RT, $t(16) = 3.68$, $p = .006$, $r = .68$; no load vs. high load: probit slope, $t(16) = 5.63$; $p < .001$, $r = .82$; accuracy, $t(16) = 4.00$, $p = .003$, $r = .71$; RT, $t(16) = 2.58$, $p = .040$, $r = .54$]. Furthermore, the crossing status difference score—that is, the crossing effect—was significantly smaller in high-load than in low-load conditions [low load vs. high load: probit slope, $t(16) = 2.44$, $p = .027$, $r = .52$; accuracy, $t(16) = 2.28$, $p = .037$, $r = .49$; see Fig. 4].

Analysis 2: Influences of working memory type on tactile localization Repeated measures ANOVAs of the same TOJ data, but with crossing status and WM type as factors, revealed a significant main effect of crossing status [probit slope, $F(1, 16) = 108.06$, $p < .001$, $\eta_g^2 = .52$; accuracy, $F(1, 16) = 73.25$, $p < .001$, $\eta_g^2 = .59$; RT, $F(1, 16) = 53.43$, $p < .001$, $\eta_g^2 = .11$], a significant main effect of WM type [probit slope, $F(2, 32) = 19.03$, $p < .001$, $\eta_g^2 = .20$; accuracy, $F(2, 32) = 8.15$, $p = .001$, $\eta_g^2 = .05$; RT, $F(1.24, 19.87) = 15.03$, $p = .006$, $\eta_g^2 = .15$] and a significant interaction between those factors [probit slope, $F(1.46, 23.35) = 18.38$, $p < .001$, $\eta_g^2 = .20$; accuracy, $F(2, 32) = 9.98$, $p = .004$, $\eta_g^2 = .06$; RT, $F(2, 32) = 6.60$, $p = .003$, $\eta_g^2 = .01$]. Post hoc analysis confirmed that the effect of crossing status was reduced under the dual-task (i.e., under verbal and spatial load) conditions, as compared with the single-task (i.e., no-load) condition [no load vs. verbal load: probit slope, $t(16) = 5.21$, $p < .001$, $r = .79$; accuracy, $t(16) = 2.61$, $p = .038$, $r = .55$; RT, $t(16) = 3.28$, $p = .014$, $r = .63$; no load vs. spatial load: probit slope, $t(16) = 4.19$, $p = .001$, $r = .72$; accuracy, $t(16) = 4.14$, $p = .002$, $r = .72$; RT, $t(16) = 2.68$, $p = .033$, $r = .56$]. The size of the crossing effect did not significantly differ between verbal and spatial load conditions (verbal load vs. spatial load: probit slope, $r = .10$; accuracy, $r = .40$; RT, $r < .01$; Fig. 4).

Analysis 3: Interactions between influences of load level and WM type on tactile localization Repeated measures ANOVAs with crossing status, load level, and WM type as factors were conducted on the TOJ data of the dual-task experiments (Experiments 2.3 and 2.4). This analysis confirmed a significant main effect of crossing status [probit slope: $F(1, 16) = 60.06$, p $< .001$, $\eta_g^2 = .37$; accuracy, $F(1, 16) = 60.42$, $p < .001$, $\eta_g^2 = .50$; RT, $F(1, 16) = 40.85$, $p < .001$, $\eta_g^2 = .06$], a significant main effect of WM type [probit slope, $F(1, 16) = 6.26$, $p = .024$, $\eta_g^2 = .05$; accuracy, $F(1, 16) = 9.83$, $p = .006$, $\eta_g^2 = .03$; RT, $F(1, 16) = 9.72$, $p = .007$, $\eta_g^2 = .02$], and a significant interaction between crossing status and load level [accuracy: $F(1, 16) = 5.05$, $p = .039$, $\eta_g^2 < .01$]. TOJ performance was reduced in crossed, as compared with uncrossed, conditions, and the crossing effect was smaller in high-load than in low-load conditions. Furthermore, TOJ performance was reduced in verbal load, as compared with spatial load, experiments (Table 4). The analysis of probit slope values additionally revealed a significant interaction between all three factors [probit slope: $F(1, 16) = 7.09$, $p = .013$, $\eta_g^2 = .03$] and a significant two-way interaction between load level and WM type [probit slope: $F(1, 16) = 11.22$, $p = .004$, $\eta_g^2 = .04$]. Post hoc conducted pairwise t-tests confirmed significant differences only for comparisons between uncrossed performance in one and crossed performance in another WM condition (Table 5). To alternatively test this result, we conducted pairwise t-tests on the crossing status difference score (uncrossed − crossed), which did not show significant differences for any of the four contrasts after correction for multiple comparisons.

Analyses of item recognition data

Performance in the single-task experiment: Experiment 2.2 Repeated measures ANOVAs with load level and WM

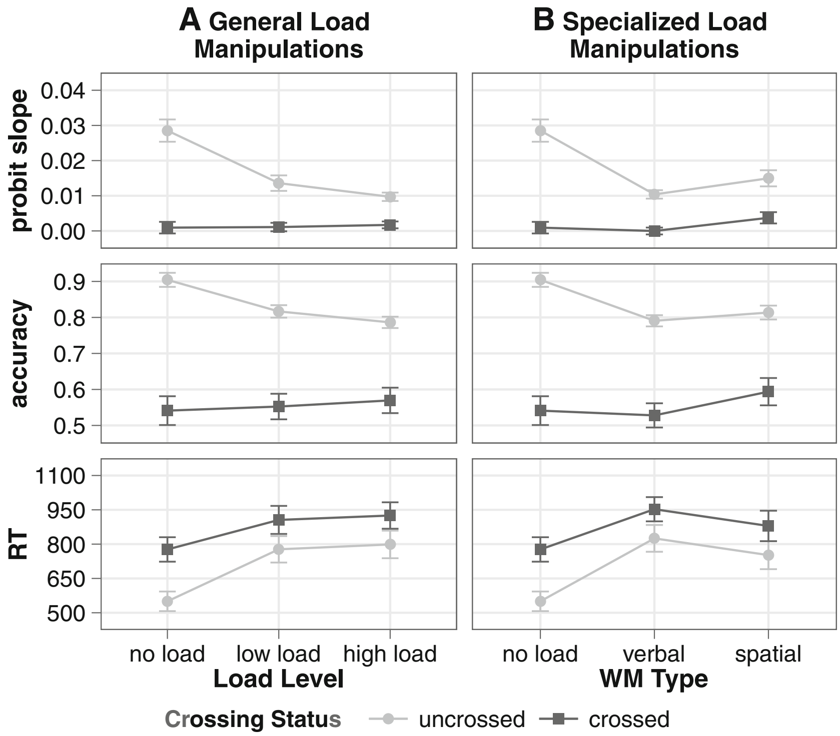

Fig. 4 Mean slopes, accuracies, and reaction times (RTs) for temporal order judgment (TOJ) performance in Study 2: TOJ performance is viewed from two perspectives: processing load level (**a**) and working memory type (**b**). All measures are shown separately for crossed (light gray) and uncrossed (dark gray) posture conditions. Error bars show standard errors

type as factors showed a significant main effect of load level on accuracy, $F(1, 16) = 120.55$, $p < .001$, $\eta_g^2 = .43$, and RT, $F(1, 16) = 7.52$, $p = .014$, $\eta_g^2 = .02$. Responses were less accurate and slower in high-load conditions than in low-load conditions (Table 6).

Performance in the dual-task experiments: Experiments 2.3 and 2.4 Repeated measures ANOVAs with crossing status, load level, and WM type as factors showed a significant main effect of load level on accuracy, $F(1, 16) = 203.44$, $p < .001$, $\eta_g^2 = .49$, and RT, $F(1, 16) = 24.35$, $p = .001$, $\eta_g^2 = 0.09$, and a main effect of WM type, $F(1, 16) = 6.00$, $p = .026$, $\eta_g^2 = .03$, on RT. Responses were slower in high-load conditions, as compared with low-load conditions, and in the verbal task, as compared with the spatial task. As intended by the adaptive procedure, accuracy was higher in low-load than in high-load conditions (Table 6).

Discussion

Study 2 tested the effect of processing load on the influence of the external coordinates of touch on tactile localization as assessed with the crossing effect in a tactile TOJ task. In contrast to Study 1, the amount of WM load was controlled

Table 4 Temporal order judgment performance in the dual-task experiments of Study 2 (Experiments 2.3 and 2.4)

Crossing Status	Load Magnitude	WM Type	Slope	Accuracy	RT
Uncrossed	low load	verbal	0.0193 (0.0027)	0.83 (0.02)	809.79 (58.24)
Crossed	low load	verbal	0.0006 (0.0021)	0.52 (0.04)	933.44 (54.78)
Uncrossed	high load	verbal	0.0102 (0.0019)	0.75 (0.02)	844.51 (63.95)
Crossed	high load	verbal	0.0005 (0.0008)	0.54 (0.03)	972.87 (57.24)
Uncrossed	low load	spatial	0.0165 (0.0026)	0.81 (0.02)	746.94 (62.78)
Crossed	low load	spatial	0.0042 (0.0018)	0.59 (0.04)	879.30 (72.73)
Uncrossed	high load	spatial	0.0205 (0.0032)	0.82 (0.02)	757.37 (60.92)
Crossed	high load	spatial	0.0054 (0.0022)	0.60 (0.04)	880.30 (63.60)

Note. Mean values and standard errors (in parentheses) are reported

Table 5 Results of the post hoc analysis of temporal order judgment performance in the dual-task conditions (Study 2, probit slopes)

	Low Load Verbal Uncrossed	High Load Verbal Uncrossed	Low Load Spatial Uncrossed	High Load Spatial Uncrossed	Low Load Verbal Crossed	High Load Verbal Crossed	Low Load Spatial Crossed
High-load verbal uncrossed	$t(16)=2.71$ $p=.186$						
Low-load spatial uncrossed	$t(16)=1.27$ $p=.673$	$t(16)=1.92$ $p=.439$					
High-load spatial uncrossed	$t(16)=0.42$ $p=1.000$	$t(16)=2.79$ $p=.170$	$t(16)=2.51$ $p=.208$				
Low-load verbal crossed	$t(16)=6.02$ **$p<.001$**	$t(16)=3.54$ **$p=.041$**	$t(16)=7.98$ **$p<.001$**	$t(16)=6.85$ **$p<.001$**			
High-load verbal crossed	$t(16)=6.55$ **$p<.001$**	$t(16)=5.03$ **$p=.002$**	$t(16)=6.54$ **$p<.001$**	$t(16)=6.40$ **$p<.001$**	$t(16)=0.06$ $p=1.000$		
Low-load spatial crossed	$t(16)=4.99$ **$p=.002$**	$t(16)=2.34$ $p=.228$	$t(16)=5.81$ **$p=.001$**	$t(16)=6.66$ **$p<.001$**	$t(16)=2.66$ $p=.186$	$t(16)=2.51$ $p=.208$	
High-load spatial crossed	$t(16)=4.06$ **$p=.015$**	$t(16)=1.70$ $p=.546$	$t(16)=4.75$ **$p=.004$**	$t(16)=5.69$ **$p=.001$**	$t(16)=3.09$ $p=.098$	$t(16)=2.68$ $p=.186$	$t(16)=1.44$ $p=.673$

Note. p-values have been corrected for multiple comparisons, following Holm (1979)

and individually adjusted by an adaptive procedure in Study 2. As in Study 1, the size of the crossing effect decreased when processing load, in the shape of a requirement to coordinate two tasks, was added to the TOJ task. Moreover, the crossing effect further decreased with an increase in WM load. Importantly, as in Study 1, the type of WM did not influence the size of the crossing effect.

In contrast to Study 1, crossed hands performance remained constant at a relatively low level throughout all conditions in this study. To compare both studies, we looked at the crossed hands performance of participants whose performance was better than chance level (8 participants with an average accuracy above 55 % correct). Performance of this subgroup improved numerically with increased processing load (64 % correct responses in the no-load conditions, 68 % correct responses in the low-load conditions, and 71 % correct responses in the high-load conditions, $F(2, 14) = 1.46$, $p > .010$). This performance increment indicates that participants who were able to perform above chance level with crossed hands did not show a performance impairment under load in the crossed conditions. This rules out the possibility that crossed hands performance was unimpaired by general task difficulty simply because performance was at floor level in crossed conditions.

In this study, the crossing effect not only was reduced by the introduction of the WM task, but also was modulated by the difficulty of this secondary task. Thus, we are now able to exclude that tactile localization interacted only with non-WM-specific top-down processes such as task coordination, which might play an additional role in the comparison between single-task and dual-task conditions. Notably, any modulation of the crossing effect by a top-down process contradicts the full automaticity of tactile remapping and coordinate integration.

Table 6 Mean values and standard errors in the item recognition task (Study 2)

Load Level	WM Type	Crossing Status	Accuracy	RT
Single-task condition (Experiment 2.2)				
Load Level	WM Type		Accuracy	RT
Low load	verbal		0.92 (0.02)	1,233.63 (94.69)
High load	verbal		0.79 (0.01)	1,360.96 (82.97)
Low load	spatial		0.89 (0.02)	1,257.74 (89.97)
High load	spatial		0.79 (0.02)	1,336.21 (78.36)
Dual-task condition (Experiments 2.3 and 2.4)				
Load Level	WM Type	Crossing Status	Accuracy	RT
Low load	verbal	uncrossed	0.91 (0.01)	1154.28 (53.94)
Low load	verbal	crossed	0.89 (0.02)	1186.50 (51.73)
High load	verbal	uncrossed	0.75 (0.01)	1322.57 (70.96)
High load	verbal	crossed	0.75 (0.02)	1291.16 (59.90)
Low load	spatial	uncrossed	0.89 (0.01)	1102.59 (40.11)
Low load	spatial	crossed	0.87 (0.03)	1122.07 (42.20)
High load	spatial	uncrossed	0.76 (0.02)	1232.87 (60.30)
High load	spatial	crossed	0.74 (0.02)	1223.65 (50.30)

Note. Standard errors are shown in parentheses

General discussion

The present study examined whether tactile remapping and coordinate integration for touch localization are automatic processes. To this aim, we tested the influence of concurrent processing load on the crossing effect—that is, the performance impairment in crossed, as compared with uncrossed, postures in tactile TOJ. In both Study 1 and Study 2, the crossing effect was significantly reduced under processing load. This modulation scaled with the amount of WM load in Study 2, when WM load was adjusted for each participant. In contrast, the influence of the two types of WM—verbal versus spatial—on the crossing effect did not differ.

In both studies, the crossing effect was reduced, rather than amplified, under processing load. At first glance, this result may seem counterintuitive. However, it is in accordance with the suggestion that tactile localization is based on both the anatomical and the external coordinates of touch (Badde et al., 2013; Badde, Röder, & Heed, 2014; Shore et al., 2002), rather than on the external coordinates alone (Kitazawa, 2002; Yamamoto & Kitazawa, 2001). When the hands are crossed, the external coordinates point toward the wrong hand. Consequently, reducing their influence should improve performance in the crossed posture. In contrast, in the uncrossed posture, the external coordinates indicate the correct response, and consequently, reducing their influence removes a redundant cue for the correct response, which potentially degrades performance with uncrossed hands. This idea is corroborated by the improvement of children's TOJ performance over the ages of 5–10. Once children have acquired the use of external coordinates in touch localization, performance improves more with uncrossed hands than it worsens with crossed hands (Pagel et al., 2009).

The modulations of the crossing effect observed in the present study suggest that the localization of touch is not fully automatic. However, there is convincing evidence that at least the initialization of tactile remapping is automatic (Azañón et al. 2010a). There are two possible ways to reconcile the previous and our present results. First, tactile remapping may be initiated automatically, but remapping may break down under conditions of high WM load (for a comparable account of audio-visual integration of speech information, see Alsius et al., 2005; Soto-Faraco, Navarra, & Alsius, 2004). Second, it is possible that only some aspects of touch localization are automatic. More specifically, the genuine remapping process may be initiated and proceed automatically, whereas the integration of the resulting external coordinates with the anatomical coordinates may be subject to top-down control (Badde et al., 2013). The present results are indeed consistent with the second account. Tactile remapping refers to the transformation of coordinates from one reference frame into another. According to this definition, tactile remapping is a spatial process. Consequently, it seems unlikely that the interference of the TOJ task that we observed in our experiments stems from an impairment of the genuine tactile remapping process, since verbal processing load modulated the crossing effect as well. In contrast, the integration process should be independent of the integrated content. Consequently, the finding that the modulation of the crossing effect was independent of WM type suggests that interference affected the integration of anatomical and external coordinates and that this integration process is, thus, under top-down control.

The level of processing load was manipulated by both introducing a WM task and manipulating the difficulty of the WM task. The crossing effect was most reliably affected by the first manipulation. On the one side, WM load differs more between single- and dual-task conditions than between low and high WM load conditions. On the other side, single- and dual-task conditions differ in the degree of required control processes for task coordination. It is possible that the integration of the anatomical and external coordinates depends predominantly on top-down processes that are involved in task coordination as well. The present data do not allow us to decide between these two accounts.

The observed modulation of multisensory integration by processing load may be associated with the parietal cortex. Tactile stimuli are represented in several different reference frames in the posterior parietal cortex (e.g., Buchholz et al., 2011, 2013). For example, it has been suggested that regions in the intraparietal sulcus might be involved in remapping tactile stimuli into external space (Azañón et al. 2010b; Bolognini & Maravita, 2007; Renzi et al., 2013). Several imaging studies have demonstrated that WM activates a network of fronto-parietal regions (Diwadkar, Carpenter, & Just, 2000; Magen, Emmanouil, McMains, Kastner, & Treisman, 2009; Todd & Marois, 2005). Moreover, functional connectivity between prefrontal and parietal cortex activity for visual and spatial WM has recently been demonstrated (Berryhill, 2012; Koch et al., 2005; Ma et al., 2012; Tseng et al., 2012).

In sum, our results contradict the automaticity of tactile localization. In the light of previous findings (Azañón et al. 2010a; Kitazawa, 2002), our findings suggest that the genuine remapping process is initiated and proceeds automatically, whereas the integration of the resulting external with the original, anatomical coordinates into a final location estimate is top-down controlled.

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References

Alsius, A., Navarra, J., Campbell, R., & Soto-Faraco, S. (2005). Audiovisual integration of speech falters under high attention demands. *Current Biology, 2*(9), 839–843. doi:10.1016/j.cub.2005.03.046

Alsius, A., Navarra, J., & Soto-Faraco, S. (2007). Attention to touch weakens audiovisual speech integration. *Experimental Brain Research, 2*(3), 399–404. doi:10.1007/s00221-007-1110-1

Azañón, E., & Soto-Faraco, S. (2007). Alleviating the 'crossed-hands' deficit by seeing uncrossed rubber hands. *Experimental Brain Research, 2*(4), 537–548. doi:10.1007/s00221-007-1011-3

Azañón, E., Camacho, K., & Soto-Faraco, S. (2010a). Tactile remapping beyond space. *European Journal of Neuroscience, 2*(10), 1858–1867. doi:10.1111/j.1460-9568.2010.07233.x

Azañón, E., Longo, M. R., Soto-Faraco, S., & Haggard, P. (2010b). The posterior parietal cortex remaps touch into external space. *Current Biology, 2*(14), 1304–1309. doi:10.1016/j.cub.2010.05.063

Baart, M., & Vroomen, J. (2010). Phonetic recalibration does not depend on working memory. *Experimental Brain Research, 2*(3), 575–582. doi:10.1007/s00221-010-2264-9

Badde, S., Heed, T., & Röder, B. (2013). Body posture affects integration of reference frames rather than coordinate transformation. (in revision).

Badde, S., Röder, B., & Heed, T. (2014). Multiple spatial representations determine touch localization on the fingers. *Journal of Experimental Psychology: Human Perception and Performance*.

Berryhill, M. E. (2012). Insights from neuropsychology: pinpointing the role of the posterior parietal cortex in episodic and working memory. *Frontiers in Integrative Neuroscience, 2,* 31. doi:10.3389/fnint.2012.00031

Bolognini, N., & Maravita, A. (2007). Proprioceptive alignment of visual and somatosensory maps in the posterior parietal cortex. *Current Biology, 2*(21), 1890–1895. doi:10.1016/j.cub.2007.09.057

Brand-D'Abrescia, M., & Lavie, N. (2008). Task coordination between and within sensory modalities: effects on distraction. *Perception & Psychophysics, 2*(3), 508–515. doi:10.3758/PP.70.3.508

Buchholz, V. N., Jensen, O., & Medendorp, W. P. (2011). Multiple reference frames in cortical oscillatory activity during tactile remapping for saccades. *Journal of Neuroscience, 2*(46), 16864–16871. doi:10.1523/JNEUROSCI.3404-11.2011

Buchholz, V. N., Jensen, O., & Medendorp, W. P. (2013). Parietal oscillations code nonvisual reach targets relative to gaze and body. *Journal of Neuroscience, 2*(8), 3492–3499. doi:10.1523/JNEUROSCI.3208-12.2013

Disbrow, E., Roberts, T., & Krubitzer, L. (2000). Somatotopic organization of cortical fields in the lateral sulcus of homo sapiens: evidence for SII and PV. *Journal of Comparative Neurology, 2*(1), 1–21.

Diwadkar, V. A., Carpenter, P. A., & Just, M. A. (2000). Collaborative activity between parietal and dorso-lateral prefrontal cortex in dynamic spatial working memory revealed by fMRI. *NeuroImage, 2*(1), 85–99. doi:10.1006/nimg.2000.0586

Driver, J., & Spence, C. (1998). Cross-modal links in spatial attention. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 353*(1373), 1319–1331. doi:10.1098/rstb.1998.0286

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 2*(2), 175–191.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using g*power 3.1: tests for correlation and regression analyses. *Behavior Research Methods, 2*(4), 1149–1160. doi:10.3758/BRM.41.4.1149

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience, 2*(6), 555–556. doi:10.1038/nn1066

Heed, T., & Röder, B. (2010). Common anatomical and external coding for hands and feet in tactile attention: evidence from event-related potentials. *Journal of Cognitive Neuroscience, 2*(1), 184–202. doi:10.1162/jocn.2008.21168

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics, 2*(2), 65–70.

Kane, M. J., Conway, A. R. A., Miura, T. K., & Colflesh, G. J. H. (2007). Working memory, attention control, and the n-back task: a question of construct validity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 2*(3), 615–622. doi:10.1037/0278-7393.33.3.615

Kesten, H. (1958). Accelerated stochastic approximation. *Annals of Mathematical Statistics, 2*(1), 41–59.

Kitazawa, S. (2002). Where conscious sensation takes place. *Consciousness and Cognition, 2*(3), 475–477. doi:10.1016/S1053-8100(02)00031-4

Koch, G., Oliveri, M., Torriero, S., Carlesimo, G. A., Turriziani, P., & Caltagirone, C. (2005). rTMS evidence of different delay and decision processes in a fronto-parietal neuronal network activated during spatial working memory. *NeuroImage, 2*(1), 34–39. doi:10.1016/j.neuroimage.2004.09.042

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 2*(3), 339–354. doi:10.1037/0096-3445.133.3.339

Logan, G. D. (1979). On the use of a concurrent memory load to measure attention and automaticity. *Journal of Experimental Psychology: Human Perception and Performance, 2*(2), 189–207. doi:10.1037/0096-1523.5.2.189

Ma, L., Steinberg, J. L., Hasan, K. M., Narayana, P. A., Kramer, L. A., & Moeller, F. G. (2012). Working memory load modulation of parieto-frontal connections: evidence from dynamic causal modeling. *Human Brain Mapping, 2*(8), 1850–1867. doi:10.1002/hbm.21329

Magen, H., Emmanouil, T. A., McMains, S. A., Kastner, S., & Treisman, A. (2009). Attentional demands predict short-term memory load response in posterior parietal cortex. *Neuropsychologia, 47*(8–9), 1790–1798. doi:10.1016/j.neuropsychologia.2009.02.015

Maxwell, S., & Delaney, H. 2004. Designing experiments and analyzing data: A model comparison perspective (Vol. 1). Lawrence Erlbaum.

Moors, A., & De Houwer, J. (2006). Automaticity: a theoretical and conceptual analysis. *Psychological Bulletin, 2*(2), 297–326. doi:10.1037/0033-2909.132.2.297

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping, 2*(1), 46–59. doi:10.1002/hbm.20131

Pagel, B., Heed, T. & Röder, B. (2009) Change of reference frame for tactile localization during child development. *Development of Science 12,* 929–937.

Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain, 2*(4), 389–443. doi:10.1093/brain/60.4.389

Posner, M., & Snyder, C. (1975). Attention and cognitive control. In R. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 55–85). Hillsdale: Lawrence Erlbaum Associates Inc.

Pouget, A., Ducom, J. C., Torri, J., & Bavelier, D. (2002). Multisensory spatial representations in eye-centered coordinates for reaching. *Cognition, 2*(1), B1–B11. doi:10.1016/S0010-0277(01)00163-9

Regenbogen, C., De Vos, M., Debener, S., Turetsky, B., Mößnang, C., Finkelmeyer, A., Habel, U., Neuner, I., & Kellermann, T. (2012). Auditory processing under cross-modal visual load investigated with simultaneous EEG-fMRI. *PloS one, 2*(12), e52267. doi:10.1371/journal.pone.0052267

Renzi, C., Bruns, P., Heise, K.-F., Zimerman, M., Feldheim, J.-F., Hummel, F. C., & Röder, B. (2013). Spatial remapping in the audio-tactile ventriloquism effect: A TMS investigation on the role of the ventral intraparietal area. *Journal of Cognitive Neuroscience*. doi:10.1162/jocna00362

Robbins, H., & Monro, S. (1951). A stochastic approximation method. *Annals of Mathematical Statistics, 2*(3), 400–407.

Röder, B., Spence, C., & Rösler, F. (2002). Assessing the effect of posture change on tactile inhibition-of-return. *Experimental Brain Research, 2*(4), 453–462. doi:10.1007/s00221-002-1019-7

Röder, B., Rösler, F., & Spence, C. (2004). Early vision impairs tactile perception in the blind. *Current Biology, 2*(2), 121–124. doi:10.1016/S0960-9822(03)00984-9

Röder, B., Föcker, J., Hötting, K., & Spence, C. (2008). Spatial coordinate systems for tactile spatial attention depend on developmental vision: evidence from event-related potentials in sighted and congenitally blind adult humans. *European Journal of Neuroscience, 2*(3), 475–483. doi:10.1111/j.1460-9568.2008.06352.x

Röder, B., Pagel, B., & Heed, T. (2013). The implicit use of spatial information develops later for crossmodal than for intramodal temporal processing. *Cognition, 2*(2), 301–306. doi:10.1016/j.cognition.2012.09.009

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. detection, search, and attention. *Psychological Review, 2*(1), 1–66. doi:10.1037/0033-295X.84.1.1

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. perceptual learning, automatic attending and a general theory. *Psychological Review, 2*(2), 127–190. doi:10.1037/0033-295X.84.2.127

Shore, D. I., Spry, E., & Spence, C. (2002). Confusing the mind by crossing the hands. *Cognitive Brain Research, 2*(1), 153–163. doi:10.1016/S0926-6410(02)00070-8

Sober, S. J., & Sabes, P. N. (2005). Flexible strategies for sensory integration during motor planning. *Nature Neuroscience, 2*(4), 490–497. doi:10.1038/nn1427

Soto-Faraco, S., Navarra, J., & Alsius, A. (2004). Assessing automaticity in audiovisual speech integration: evidence from the speeded classification task. *Cognition, 2*(3), B13–B23. doi:10.1016/j.cognition.2003.10.005

Sternberg, S. (1966). High-speed scanning in human memory. *Science, 2*(3736), 652–654. doi:10.1126/science.153.3736.652

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in Cognitive Science, 2*(9), 400–410. doi:10.1016/j.tics.2010.06.008

Todd, J. J., & Marois, R. (2005). Posterior parietal cortex activity predicts individual differences in visual short-term memory capacity. *Cognitive, Affective, & Behavioral Neuroscience, 2*(2), 144–155. doi:10.3758/CABN.5.2.144

Tseng, P., Hsu, T.-Y., Chang, C.-F., Tzeng, O. J. L., Hung, D. L., Muggleton, N. G., Walsh, V., Liang, W.-K., kuen Cheng, S., & Juan, C.-H. (2012). Unleashing potential: transcranial direct current stimulation over the right posterior parietal cortex improves change detection in low-performing individuals. *Journal of Neuroscience, 2*(31), 10554–10561. doi:10.1523/JNEUROSCI.0362-12.2012

Wada, M., Yamamoto, S., & Kitazawa, S. (2004). Effects of handedness on tactile temporal order judgment. *Neuropsychologia, 2*(14), 1887–1895. doi:10.1016/j.neuropsychologia.2004.05.009

World Medical Association. (2008). Declaration of Helsinki. Ethical principles for medical research involving human subjects. *Bull World Health Organ*, *2*(4), 373–374. http://www.wma.net/en/30publications/10policies/b3/index.html

Yamamoto, S., & Kitazawa, S. (2001). Reversal of subjective temporal order due to arm crossing. *Nature Neuroscience, 2*(7), 759–765. doi:10.1038/89559

Yang, T. T. (1993). Noninvasive somatosensory homunculus mapping in humans by using a large-array biomagnetometer. *Proceedings of the National Academy of Sciences, 2*(7), 3098–3102. doi:10.1073/pnas.90.7.3098

Zimmer, U., & Macaluso, E. (2007). Processing of multisensory spatial congruency can be dissociated from working memory and visuo-spatial attention. *European Journal of Neuroscience, 2*(6), 1681–1691. doi:10.1111/j.1460-9568.2007.05784.x