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The effects of voluntary movements on auditory–haptic and haptic–haptic temporal order judgments

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ABSTRACT

In two experiments we investigated the effects of voluntary movements on temporal haptic perception. Measures of sensitivity (JND) and temporal alignment (PSS) were obtained from temporal order judgments made on intermodal auditory–haptic (Experiment 1) or intramodal haptic (Experiment 2) stimulus pairs under three movement conditions. In the baseline, static condition, the arm of the participants remained stationary. In the passive condition, the arm was displaced by a servo-controlled motorized device. In the active condition, the participants moved voluntarily. The auditory stimulus was a short, 500 Hz tone presented over headphones and the haptic stimulus was a brief suprathreshold force pulse applied to the tip of the index finger orthogonally to the finger movement. Active movement did not significantly affect discrimination sensitivity on the auditory–haptic stimulus pairs, whereas it significantly improved sensitivity in the case of the haptic stimulus pair, demonstrating a key role for motor command information in temporal sensitivity in the haptic system. Points of subjective simultaneity were by-and-large coincident with physical simultaneity, with one striking exception in the passive condition with the auditory–haptic stimulus pair. In the latter case, the haptic stimulus had to be presented 45 ms before the auditory stimulus in order to obtain subjective simultaneity. A model is proposed to explain the discrimination performance.

1. Introduction

Tactile sensations arise when we are the object of touch (i.e., passive touch) or when we are the agent of touch (i.e., active touch, or haptics) (Grünwald, 2008; Lederman & Klatzky, 2009). In many circumstances, it is known that touch sensations depend not only on cutaneous inputs, but also on proprioceptive information, motor planning, motor execution, inputs from other modalities, endogenous states, and other sources (Bays, Flanagan, & Wolpert, 2006; Behrmann, Kosslyn, & Jeannerod, 1995; Carter, Konkle, Wang, Hayward, & Moore, 2008; Smith, Chapman, Donati, Fortier-Poisson, & Hayward, 2009; Stein & Meredith, 1993; Voss, Bays, Rothwell, & Wolpert, 2007). Motor commands are issued during voluntary movements. These commands are thought to be available to the central nervous system in the form of so-called efference copies, (Von Holst & Mittelstaedt, 1950, for a review see Cullen, 2004), and are instrumental in anticipating the sensory consequences of voluntary movement (e.g., Blakemore, Frith, & Wolpert, 1999).

The present focus is on haptic temporal perception during active movements. Temporal perception has received considerable attention for purely haptic stimulation (e.g., Hirsh & Sherrick, 1961; Marks et al., 1982) as well as for intermodal combinations involving the haptic system (see Keetels & Vroomen, 2012; Occelli, Spence, & Zampini, 2011 for reviews). Many of the previous studies investigated haptic temporal perception when the participants were exposed to stimuli resulting from the activity of an external agent. The haptic system, however, most frequently operates under an active condition, that is, when stimulation occurs during the production of voluntary movement. We therefore wondered whether voluntary movements could play a role in the acuity of haptic temporal perception.

A common experimental paradigm for studying temporal perceptual processes is the temporal order judgment (TOJ) task. In this task two stimuli are presented at various onset asynchronies (SOA) and participants judge which one of the two came first. Another task is the simultaneity judgment (SJ), in which participants judge whether the two had been presented simultaneously or not. Two distinct measures of performance can be derived from the behavior of observers (Coren, Ward, & Enns, 1999). The first measure is the just-noticeable-difference (JND),

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which is the smallest temporal interval an observer can reliably distinguish. The JND, therefore, is a measure of the observer's 'temporal sensitivity'. The second measure is the point of subjective simultaneity (PSS), where the observer is maximally unsure about the temporal order of the stimuli. A non-zero PSS means that one of the stimuli has to be presented earlier than the other for the two to be perceived as occurring simultaneously. In other words, the PSS is a measure of the internal 'temporal alignment' of the sensory signals. Although, the TOJ and SJ should theoretically provide the same estimates for the JND and PSS, they rarely do so. In particular, because of the SJ's dependence on internal decision criteria, the TOJ is the preferred method (Keetels & Vroomen, 2012).

When studying the effects of movement on temporal perception it is possible to distinguish voluntary (i.e., active) movements from the same physical movements performed without the motor command information. This testing condition can be achieved by having the movement produced through the use of a robotic device. Unfortunately, the term 'passive' is also often used to describe conditions in which the stimulus is applied to the participants' skin without any movement on their part whatsoever. We will refer to this latter condition as a 'static' condition.

Only a few studies have looked at the consequences of voluntary movement on the temporal processing of sensory inputs. They are summarized in Table 1. Some of these studies investigated the perception of temporal ordering of intermodal stimulus pairs, i.e., between haptic inputs on the one hand and auditory (Adelstein, Begault, Anderson, & Wenzel, 2003; Kitagawa, Kato, & Kashino, 2009; Wenke & Haggard, 2009) or visual (Shi, Hirche, Schneider, & Muller, 2008; Vogels, 2004) inputs on the other. Yet others have been concerned with temporal processing within the haptic sense (Wenke & Haggard, 2009; Winter, Harrar, Gozdzik, & Harris, 2008). Vogels (2004) found that the JND for asynchronies between haptic and visual stimuli was slightly, yet significantly, higher when moving actively in comparison to a static condition. Shi et al. (2008), on the other hand, found that voluntary movements significantly reduced the JND. In addition, they observed that moving actively produced a temporal shift in the perceptual alignment between the two senses. When the participants did not move their arms, the visual stimuli had to be presented on average 20 ms before the haptic stimulus in order for the two to be perceived as simultaneous. With active arm movements this value was reduced to around 5 ms. The source of the contrasting results in JND between the Shi et al. and the Vogels studies can likely be found in methodological differences. Vogels (2004) employed an SJ task and used a cross-experiment comparison to infer effects of movement, which make the study susceptible to decisional criteria and order effects, respectively. Shi et al. (2008) used a TOJ task and a balanced, within-subjects design, which is arguably a more appropriate procedure. Shi et al. attributed the difference mostly to the fact that, in their study, the visual and haptic stimuli were spatially coincident, whereas in Vogels' experiment the visual and haptic stimuli were spatially disparate. Winter et al. (2008) studied the effect of voluntary movements on intramodal haptic temporal alignment. Using an SJ task, they asked participants to voluntarily tap a Morse key with their right index finger while statically receiving delayed taps on the left index finger. They observed that a statically felt stimulus had to be presented about 30 ms before the actively produced stimulus in order for the two to be perceived as being simultaneous, although direct statistical significance could not be achieved. Because in this procedure the static and active stimuli were compared directly on a trial-by-trial basis, it was not possible to determine whether there was a difference in discrimination sensitivity between the two.

Table 1
Qualitative summary of previous studies on the effect of voluntary movement on temporal perception. Entries are in alphabetical order. The second column (n) indicates the number of participants in the study. For the movement conditions "+" indicates that the corresponding condition was included in the study. Tasks were either temporal order judgments (TOJ) or simultaneity judgments (SJ) (see Introduction). Stimulus pairs: AH, auditory–haptic; VH, visuo–haptic; HH, haptic–haptic. For the effect on JND, "+" indicates that performance improved (lower JND) and "−" that performance was impaired (higher JND). A question mark indicates that the effect could not (reliably) be determined from the study or was not reported.

Study	*n*	Movement conditions			Task	Stimulus pair	Effect active movement	
		Static	Passive	Active			JND	PSS*
Adelstein et al., 2003	12	−	−	+	TOJ	AH	?	?
Kitagawa et al., 2009	11	+	+	+	TOJ	AH	+	?
Shi et al., 2008	9	+	−	+	TOJ	VH	+	V→H
Vogels, 2004	5	+	−	+	SJ	VH	−	H→V ?
Wenke & Haggard, 2009	19	−	+	+	SJ	HH	−	?
Winter et al., 2008	13	+	−	+	SJ	HH	?	Static→Active

* Entries with an arrow indicate the stimulus order at PSS.

The studies discussed so far employed static and active conditions only. These conditions do not test whether differences in performance may be attributed to proprioceptive signals arising from the movement *per se* or from an active, voluntary arm movement which also includes motor command information (efference copy). To address this limitation, Kitagawa et al. (2009) asked participants to make auditory–haptic temporal order judgments under static and active, as well as passive movements. In the static condition, a motorized device tapped the participants' index fingers. In the passive condition, the finger was moved by a motorized device. In the active condition, the participants hit a button voluntarily. They found an increase in sensitivity for the active 'voluntary' condition by as much as 45% relative to the static condition. The inclusion of a passive 'involuntary' condition allowed for the assessment of the contribution of the finger movement in the absence of an efference copy informing the central nervous system in advance of the execution of the occurrence of movement. Performance in this Passive condition did not differ significantly from the static condition. The authors concluded that the improved temporal discrimination performance in active touch could be attributed to an efference copy rather than due to movement *per se*. Wenke and Haggard (2009) also employed a passive condition to study the effects of voluntary movement on haptic temporal discrimination. They found that voluntary movements impaired the temporal discrimination of tactile stimuli applied to the index and the middle finger of the same moving hand, but only when the stimulation occurred close in time to the movement (around 150 ms).

Thus, our current knowledge on the effects of voluntary movements on temporal perception is sparse and divergent. Voluntary movement has been found to either improve (Kitagawa et al., 2009; Shi et al., 2008) or to worsen temporal discrimination (Vogels, 2004; Wenke & Haggard, 2009). Some studies report JNDs only and others PSSs only, and these measures are either based on TOJ tasks (Kitagawa et al., 2009; Shi et al., 2008) or SJ tasks (Vogels, 2004; Wenke & Haggard, 2009; Winter et al., 2008). A further complication is that some studies used intermodal stimulus pairs whereas others used intramodal stimuli. Finally, only the Kitagawa et al. (2009) and Wenke and Haggard (2009) studies created conditions that could potentially distinguish between the contributions of movements *per se* and motor command information.

The aim of the present study was to use a single paradigm, the TOJ task, to investigate the effect of voluntary movements on haptic temporal perception. The task was performed under static, passive, and active movement conditions in order to distinguish between the contributions of the cutaneous, proprioceptive, and motor command information. In the baseline, static condition, the right arm of the participants remained stationary. In the passive condition, the arm was displaced by a servo-controlled motorized device, which also delivered haptic stimuli. In the active condition, the participants moved voluntarily as the device was programmed to offer negligible resistance to movement. Care was taken to match the conditions in terms of movement speed and intensity of the haptic stimuli. To determine the effect of the particular stimulus pair used we performed two experiments. In Experiment 1, we used an intermodal stimulus pair where the occurrence of the haptic stimulus was judged in relation to the occurrence of an auditory stimulus. In Experiment 2, we used an intramodal stimulus pair where the occurrence of a haptic stimulus received by a moving hand was compared to a similar haptic stimulus applied to the contralateral static hand. Finally, because the PSS and JND are distinct measures of temporal perception we report and discuss both individually.

The divergence of results in the literature precludes the formulation of clear predictions regarding the effect of active arm movements on haptic temporal perception, particularly for PSEs. Nevertheless, for JNDs, three possible patterns of results can be anticipated. It could be that performance improves during voluntary movement (i.e., JNDs become smaller; Kitagawa et al., 2009; Shi et al., 2008). Such an outcome would argue in favor of a mechanism that takes motor command information into account in order to enhance the temporal acuity of the haptic system. On the other hand, performance could worsen (Vogels, 2004; Wenke & Haggard, 2009), which could then be related to earlier physiological studies showing that the transmission of tactile inputs is diminished, or "gated", during the course of active movements (e.g., Chapman, 1994). Lastly, voluntary arm movement could have no effect on performance.

2. Experiment 1

The first experiment addressed the temporal discrimination of auditory and haptic stimuli during voluntary movements. The experiment revisited the study of Kitagawa et al. (2009) with several methodological differences. Haptic pulse stimuli were produced at random instants during movement and in a direction orthogonal to the movement. The resulting stimulus situation was akin to exploring an unknown smooth surface and unexpectedly "bumping into a rough spot." These testing conditions minimized possible confounds arising from anticipation and mental motor imagery (Behrmann et al., 1995). The effect was to reduce the apparent causality between motor efference and sensory afference.

2.1. Method

2.1.1. Participants

Twenty-four participants (15 female, 18–36 years) completed the experiment and were paid for their participation. None of them had had any extensive experience with psychophysical procedures. Participants gave their informed consent before participating. Procedures for this and the next experiment were in accordance with the guidelines set out in the Declaration of Helsinki. The McGill University ethics committee approved the experimental protocol.

2.1.2. Apparatus and stimuli

The main apparatus was a Pantograph, a high-performance haptic device (Fig. 1a; see also Campion, Wang, & Hayward, 2005, for a more complete description), developed for rendering virtual surfaces. However, in the present study the device's capabilities were exploited to generate a force pulse on the finger tip and to move the participants' arm. Otherwise, no surface was rendered and the participant felt a smooth surface when engaging with the device. The Pantograph can produce forces of up to 2 N in a two-dimensional workspace of 100×60 mm and has a flat response from DC to 400 Hz. The torque commands were processed by a low pass reconstruction filter, so that the commands to the motors matched the mechanical bandwidth of the system. To further reduce possible stimulus artefacts, the device was retrofitted with viscous dampers based on the principle of eddy current brakes (Gosline, Campion, & Hayward, 2006). The main purpose of these devices was to increase the passivity margin of the closed-loop control when employed to guide the participants in the passive condition and guarantee the absence of artefacts that are often present during the closed-loop control of haptic interfaces (Hayward & MacLean, 2007, Section 4). In the passive testing condition (see below) the haptic device controlled the position of the participant's finger by feedback servo control. In the active condition, the device offered negligible resistance to movement. The participants placed their right index finger on a small horizontal surface and an adjustable Velcro strap helped to keep the finger in place. The entire setup was hidden from view by placing it in a dark box with an aperture for the participant's arm.

The operation of the Pantograph device was quiet since it has no mechanical transmissions, however, a faint acoustic 'tick' could emanate from the actuators when producing a force pulse, which may taint the results. Participants therefore wore sound isolation headphones (Direct Sound EX-29) playing a white-noise background that effectively masked any sounds made by the device. The auditory stimulus was a 100 ms, 500 Hz tone superimposed onto the masking noise. The haptic stimulus consisted of a 10 ms force pulse with an amplitude of 1.4 N, applied orthogonally to the finger movement (see Fig. 1c). The haptic and the auditory stimuli were suprathreshold.

2.1.3. Procedure

The participant engaged in an unspeeded temporal order judgment (TOJ) task and was asked to indicate whether the auditory or the haptic stimulus had been presented first. On each trial an auditory–haptic stimulus pair was presented with one of nine stimulus onset asynchronies (SOA) taken from the interval of −300 ms to +300 ms in steps of 75 ms. The task was administered under three different conditions, which were counterbalanced across participants and run twice according to an ABC–CBA scheme. Thus, there were a total of six, relatively short (approx. 5 min), blocks of randomized trials. There were 10 replications of each SOA per block, giving a total of 180 trials for each of the three conditions, and a grand total of 540 trials per participant.

In the static condition, the participants placed their right index finger on the finger pad, and remained stationary throughout. Throughout the experiment the arm was comfortably supported by soft gel packs near the right elbow. A trial in the static condition proceeded as follows. A stimulus pair was presented and the program controlling the experimental procedure waited for the participant to enter their response on a keyboard with their left hand. After the answer was registered there was a random interval between 1100 and 1200 ms before the next stimulus pair was presented.

In the two conditions with movement the participants were required to move forearm, hand, and finger as one, and adherence was checked by the experimenter. The gel packs near the right elbow now also served as the pivot point. The starting position of the arm was near the left boundary of the Pantograph's work surface and stimuli were presented as the arm moved from left to right (see Fig. 1c). A haptic stimulus was produced only if the finger was within the central 60 mm-wide band of the work surface. The onset of the first stimulus in a pair occurred with a random delay (100–200 ms) after the finger had moved inside this active area. The entire stimulus pair was presented well before the movement of the hand had ceased.

In the passive condition the participant's arm movements were controlled by the Pantograph device. The velocity was arbitrarily set to 70 mm/s, which was considered to be a comfortable speed and representative of normal surface exploration. After the device had moved the arm and delivered the haptic stimulus it waited in the rightmost position until the participant entered a response, after

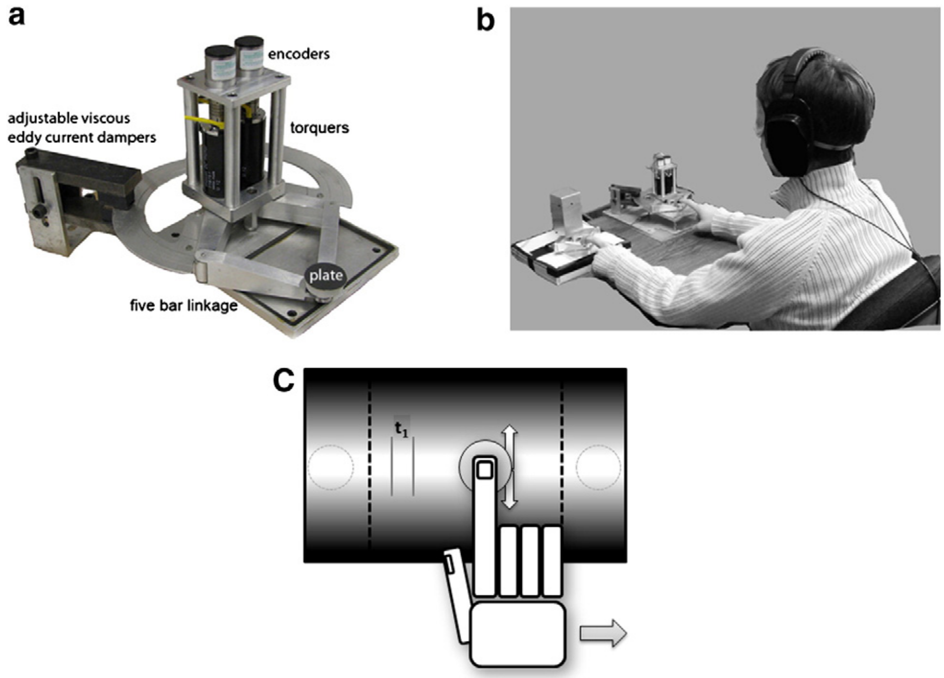

Fig. 1. Apparatus and tactile stimulus presentation. (a) The Pantograph (with eddy current brakes). It features a planar parallel mechanism (five bar linkage) with a nonslip plate on which the finger pad rests. Judiciously programmed tangential interaction forces at the plate have the effect of causing fingertip deformations and tactile sensations that resemble exploring real surfaces (see Campion et al., 2005, for a more detailed description of the device). (b) Setup in Experiment 2 with the two Pantographs. (c) A schematic representation (to scale) of the Pantograph during a trial in the passive and active conditions. On each trial the arm moved from the start position on the left to the end position on the right (grey dotted lines circles). The first stimulus in the pair was presented after the finger pad had entered the "active" area (dotted black vertical lines) within the window indicated by the grey vertical lines at t_1 (see also procedure for experiment 1). The double arrow represents anterior-posterior axis along which the haptic stimulus was delivered. We considered the fact that the net force pulse of the haptic stimulus could potentially be diminished due to small forces applied by the participant on the finger pad. To ensure that haptic stimuli were suprathreshold we varied the direction of the stimulus on a trial by trial basis according to the instantaneous force applied by the participant at the time of stimulus presentation. Thus, if the participant was applying a force, however slightly, away from the body the stimulus was presented away from the body as well, and vice versa. The shaded area is a cartoon (i.e., not representative of the physical parameters) of the "virtual corridor" that was put in place to ensure a smooth and linear path.

which it moved the arm back to the starting position. To initiate the next trial the participant pressed the spacebar.

In the active condition, participants were asked to voluntarily move their arms from left to right while the Pantograph ensured that the movement was performed in a straight line. That is, a "virtual corridor" constrained the fingertip movements along a straight path. To match the movement velocities in the active and passive conditions, a simple trial-to-trial feedback was provided (see also Vitello, Ernst, & Fritschi, 2006) and no stimulus was presented if the participant moved too fast (>100 mm/s) or too slowly (<40 mm/s), in which case they were required to try again. After completing the movement the participant kept their arm at the rightmost position until they entered their response, after which they moved the arm back to the starting position.

Before any data were collected the participants were familiarized with the three conditions and the different procedures by performing 15 practice trials without feedback for each condition. The SOAs were all set to 300 ms so that the task was relatively easy. During training the conditions were run in a fixed order, static, passive, and active.

2.1.4. Data analysis

Fig. 2 illustrates how the dependent measures were obtained. We first pooled the raw data for the two blocks of each condition. We calculated for each SOA the proportion of trials in which the auditory stimulus had been perceived first. Individual psychometric functions were obtained by fitting cumulative Gaussians using the software package 'psignifit' (Wichmann & Hill, 2001; see http://bootstrap-software.org/psignifit/). From the fits we calculated the PSS and JND. Statistical analyses were conducted using R (version 2.12.1). We used a significance level of 0.05.

2.2. Results and discussion

The mean JND and PSS in the three conditions are summarized in Table 2. None of the conditions produced a significant correlation between individual JNDs and PSSs, all $|\rho|<0.39$, all p-values>0.24.

For the JNDs, a one-way repeated measures ANOVA with movement condition as factor did not show a significant effect ($F(2,46)=$

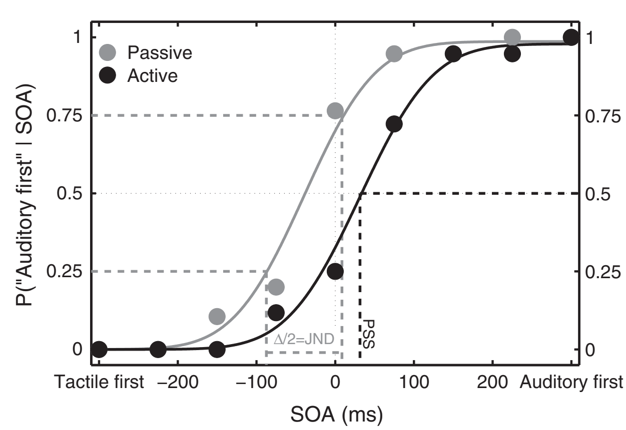

Fig. 2. An illustrative example of the analysis of the passive and active conditions for one participant. The figure demonstrates how the PSS and JND were extracted from cumulative Gaussian fits to the response data. On the abscissa are the SOAs and on the ordinate, the proportion of times that the auditory stimulus was perceived before the tactile stimulus. The solid lines are the corresponding fits, which included a nuisance parameter λ in order to account for non task-related observer lapses (Wichmann & Hill, 2001). The PSS (black dotted lines) is the SOA that corresponds to $p=0.5$. The JND (gray dotted lines) is the difference (Δ) between the SOAs corresponding to $p=0.25$ and $p=0.75$ divided by two.

Table 2
Summary of Experiment 1. A negative PSS indicates that the right hand tactile stimulus was presented before the sound. The right-most column (ρ) lists the correlation between the JND and PSS.

	JND (ms)		PSS (ms)		ρ
Movement	Mean	SE	Mean	SE	
Static	102	14	4	12	−0.11
Passive	94	9	−45	15	−0.39
Active	114	12	12	21	0.11

2.05, $p=0.14$). This lack of a difference between movement conditions is in contrast to the results obtained by Kitagawa et al. (2009) who found an improvement in their active condition. One possible cause of the difference is the predictability of the onset of the haptic stimulus. In Kitagawa et al.'s experiment there was a strong causal relationship between the onset of the haptic stimulus and the finger movement, causing the perceived time of the haptic stimulus to be predictable. Based on another experiment in which the onset of the auditory stimulus was purposefully highly predictable, Kitagawa et al. argued this predictability hypothesis could not explain the advantage for voluntary movement. However, one could counter that this manipulation of the auditory stimulus was not a strong test for the predictability hypothesis, since it does not preclude the possibility that the predictability of the onset time of the *haptic* stimulus was enhanced. Moreover, this effect may not even require the presence of the motor command information. In our experiment, the arm movement and the onset of the haptic stimulus were decoupled and therefore the causal relationship between the two was broken. This meant that the onset of the haptic stimulus was less predictable and changes in performance in the active condition were more likely to be due to the availability of motor command information.

The mean PSS for the static, passive, and active conditions were 4 ms, −45 ms, and 12 ms, respectively. A one-way repeated measures ANOVA with movement condition as factor showed a significant effect of condition ($F(2,46)=7.22$, $p=0.002$). Subsequently, Bonferroni corrected, paired *t*-tests confirmed significant differences between the passive and the static condition ($t(23)=3.56$, $p=0.002$) and between the passive and active condition ($t(23)=3.24$, $p=0.004$). There was no significant difference between the static and active conditions ($t(23)=0.005$, $p=0.99$). We tested whether the PSSs were significantly different from zero (i.e., physical simultaneity). This was the case for the passive condition ($t(23)=2.93$, $p<0.01$), but not for static ($t(23)=0.29$, $p=0.78$), or active conditions ($t(23)=0.17$, $p=0.86$). Thus, in the passive condition, the haptic stimulus had to be presented on average 45 ms before the sound in order to achieve subjective simultaneity. We defer possible explanations for this remarkable result to the General discussion.

3. Experiment 2

As discussed in the Introduction, one complicating factor in the study of the effects of voluntary movement on temporal perception is the use of intermodal (auditory–haptic, or visual–haptic) stimulus pairs in some studies and intramodal (haptic) in others. As a comparison to the intermodal stimulus pair Experiment 2 was similar to Experiment 1, but the auditory stimulus was replaced by a haptic stimulus delivered to the left hand.

3.1. Method

3.1.1. Participants

Eighteen new participants (11 female, 18 and 36 years) completed the experiment and were paid for their participation. None of them had had any extensive experience with psychophysical procedures.

3.1.2. Apparatus and stimuli

The setup of Experiment 1 was extended with a second Pantograph (see Fig. 1b) to stimulate the left hand, which was stationary at all times. The entire setup was hidden from view by placing a blindfold over the participant's eyes. Since both hands were engaged, participants entered their response using a sturdy, industrial-grade foot pedal (Immersion). The pedal comprises a mechanical toggle switch indicating its state which was polled at 1000 Hz. The left hand was always static and only the right hand moved, exactly as in Experiment 1.

Because this second device was operated in open loop, it was not retrofitted with damping hardware, and since for the two machines the signal was a short transient force pulse containing mostly high frequencies, inertial dynamics dominated the response over the viscous dynamics. Nevertheless, there was a small but invariable residual difference between the left and right stimuli—and therefore between the two hands. Because we were measuring differences between movement conditions, any small bias was second-order and had no bearing on the results.

3.1.3. Procedure

On each trial, a stimulus pair was presented with one of nine stimulus onset asynchronies (SOA; -300 ms to +300 ms in steps of 75 ms). Each SOA was tested 20 times. The participant engaged in a temporal order judgment (TOJ) task and was asked to indicate to which hand the haptic stimulus had been presented first. Before any data were collected the participants were familiarized with the three conditions and the different procedures by performing 16 practice trials for each condition. The SOAs were all set to ±300 ms so the task was relatively easy although there was no feedback. During training the conditions were run in a fixed order: static, passive and active.

3.2. Results and discussion

The mean JND and PSS in the three conditions are summarized in Table 3. In none of the conditions was there a correlation between individual PSS and JNDs, all $|\rho|<0.19$, all *p*-values>0.44.

For the JND a one-way repeated measures ANOVA with movement condition as factor showed a significant effect ($F(2,34)=9.98$, $p<0.001$). Subsequent, Bonferroni corrected, paired *t*-tests revealed significant differences between the static and the active condition ($t(17)=3.18$, $p=0.016$), and between the passive and the active condition ($t(17)=4.66$, $p<0.001$). There was no significant difference between the static and the passive condition ($t<1$). The significant improvement in the JND in the active condition in comparison to both the static and passive conditions is in contrast to Experiment 1 as well as Wenke and Haggard (2009). We return to this in the General discussion.

The mean PSS for the static, passive, and active conditions were 10 ms, 28 ms, and 16 ms, respectively. A positive value in this case meant that the stimulus to the left hand had to be presented earlier than the one to the right hand. A one-way repeated measures ANOVA with movement condition as a factor showed no significant effect ($F(2,34)=1.50$, $p=0.24$). The overall mean PSS was significantly

Table 3
Summary of Experiment 2. A positive PSS indicates that the left hand stimulus was presented before the right hand stimulus. The right-most column (ρ) lists the correlation between the JND and PSS.

	JND (ms)		PSS (ms)		ρ
Movement	Mean	SE	Mean	SE	
Static	52	3	10	7	−0.19
Passive	55	2	28	4	0.07
Active	35	3	16	6	−0.16

different from zero ($F(1,17) = 4.93$, $p = 0.04$) at around 18 ms. The finding that the overall PSS was non-zero can be attributed to the difference between the two Pantographs. That is, even though the same stimulus was commanded to both devices, it could have been sensed slightly differently at the two hands. The stimuli sensed by the right hand could be more salient and there is evidence that the processing time of a tactile stimulus depends on its saliency. For instance, Efron (1963) delivered electrical stimuli to the left and right index fingers and the participants were asked to perform a temporal order judgment. When the stimulus to the left hand was weaker it had to be presented earlier with respect to the relatively stronger right hand stimulus (by about 5 ms), and vice versa. The fact that PSSs were not different from each other across conditions suggests that the shift observed in the passive condition in Experiment 1 is restricted to intermodal stimulus conditions.

We also made comparisons between the two experiments for each condition using corrected unpaired two sample *t*-tests. The JNDs were significantly smaller in Experiment 2 in all three conditions (all t's > 3.25, all p-values < 0.003). The PSSs were significantly different between the two experiments for the passive condition ($t = 3.97$, $p < 0.001$), but not for the static and active conditions (both t's < 1).

4. General discussion

In two experiments we examined the effects of voluntary movements on temporal perception both in terms of temporal sensitivity (JNDs) and temporal alignment (PSS). The fact that we found no correlation between the JNDs and PSSs in either experiment confirms our contention that these measures reflect distinct aspects of temporal perception (see Introduction) and therefore warrant separate discussion.

A comparison between the experimental results showed that the intermodal stimulus pair (Experiment 1) produced larger JNDs than the intramodal pair (Experiment 2). This is consistent with what has been reported in the literature (Fiori, Tinazzi, Bertolasi, & Aglioti, 2003; Fujisaki & Nishida, 2009). However, the more striking and pertinent result came from the active conditions. When compared to the extant literature we found yet another pattern of effects of voluntary movements on temporal perception. For the intermodal stimulus pair, performance in the active condition was not different from either the static or passive conditions. For the intramodal stimulus pair, on the other hand, discrimination performance in the active condition was superior, not only compared to the static condition but also to the passive condition. The latter difference is important because it shows that the improvement in performance cannot be attributed to proprioceptive signals from the arm movements *per se*. This then shows, for the first time, a key role of motor command information in improving the temporal processing of proprioceptive signals.

The main results for the PSSs can be summarized as follows. For the intermodal stimulus pair we observed a significant shift in the PSS in the passive condition. That is, the haptic stimulus had to be presented 45 ms before the sound in order to reach subjective simultaneity. For the intramodal stimulus pair we did not find a significant difference between the movement conditions, and if anything, there was an overall tendency for a shift in the opposite direction.

In the following sections we discuss these main findings in more detail and address the limitations of the present study as well as the outlook it creates.

4.1. Effect of voluntary arm movement on haptic temporal sensitivity (JND)

To summarize and interpret the findings, we developed a descriptive model that is illustrated in Fig. 3. The figure illustrates the combination of two factors, movement condition (static vs. active) and the involved sensory systems (intramodal vs. intermodal). Since there was no difference in JNDs between the static and passive condition we chose the static condition as the baseline. There are two critical components, one for each factor. First, an active arm movement produces an efference copy, which is absent in the static and passive movement conditions. We postulate a process in which the utilization of the efference copy improves the processing of proprioceptive signals (e.g., Craske & Crawshaw, 1975; Gritsenko, Krouchev, & Kalaska, 2007; Winter, Allen, & Proske, 2005) and extend its range to include the temporal aspect of these signals (e.g., Miall, Weir, Wolpert, & Stein, 1993). Second, in order to make a temporal comparison of two signals they converge on a locus where the comparison is implemented. Moreover, this additional step adds processing noise (Fujisaki & Nishida, 2005; 2009).

Consider the case of *static intramodal* TOJ (Fig. 3, top left panel), which in the present conception represents the simplest scenario. The sensory signals from the haptic system are propagated directly to the perceptual process that extracts the temporal order of the two signals. For the *static intermodal* TOJ (bottom left panel), the additional step of crossmodal convergence adds processing noise to the sensory signals (i.e., the variance in the signals becomes larger). These noisier signals are then propagated to the process that performs the temporal order estimation. This additional processing noise would explain why we observe larger JNDs with intermodal stimulus pairs compared to intramodal stimulus pairs. When performing the *active intramodal* TOJ (top right panel) the influence of the efference copy becomes operational. Finally, temporal order extraction, convergence, and efference copy, come together in the *active intermodal* TOJ (bottom right panel). Critically, the model suggests that the beneficial effects of the efference copy are cancelled out by the noise added in the crossmodal convergence. The model predicts that performance on the active intermodal TOJ is either equal to, or better than *static intermodal.* However, in the case of an improvement, this would be of a smaller magnitude than for the intramodal case.

Note that the model does not incorporate the substantial physiological evidence that during active movements both cutaneous and proprioceptive inputs are attenuated, or gated (Chapman, Bushnell, Miron, Duncan, & Lund, 1987; Collins et al. 1998; Seki et al. 2003). In spite of the demonstrable physiological effects of gating, a considerable number of psychophysical studies have failed to show a difference between passive and active touch (Chapman, 1994; Chapman et al., 1987; Feine, Chapman, Lund, Duncan, & Bushnell, 1990; Konczak, Li, Tuite, & Poizner, 2008; Lamb, 1983; Lederman, 1981; Post, Zompa, & Chapman, 1994; Schwartz, Perey, & Azulay, 1975; Sciutti et al., 2010; Vega-Bermudez, Johnson, & Hsiao, 1991), suggesting that gating does not affect perception. However, more recently, careful psychophysical experiments have been reported showing that active movements indeed impair performance on *spatial* discrimination tasks. For instance, Vitello et al. (2006) reported a phenomenon they refer to as tactile suppression that is analogous to saccadic suppression. They measured the motion-direction discrimination performance for tactile stimuli moving laterally on the index finger. Performance was measured under three conditions similar to the ones in the present study; static, only tactile stimuli were presented without any movement; active, the participant made active arm movements; passive, the participant's arm was moved by a robotic device mimicking the active arm movement. In comparison to the static condition performance in the active condition was worse. Also, referring to tactile suppression of displacement, Ziat, Hayward, Chapman, Ernst, and Lenay (2010) found that when participants moved their fingers over a tactile display, a small displacement of a tactile stimulus went unnoticed. Smith et al. (2009), employing a force feedback device that can independently produce both lateral forces one the fingertip as well as horizontal displacements, report that for a horizontal displacement of a finger, categorization thresholds were higher and magnitude estimates were smaller during active

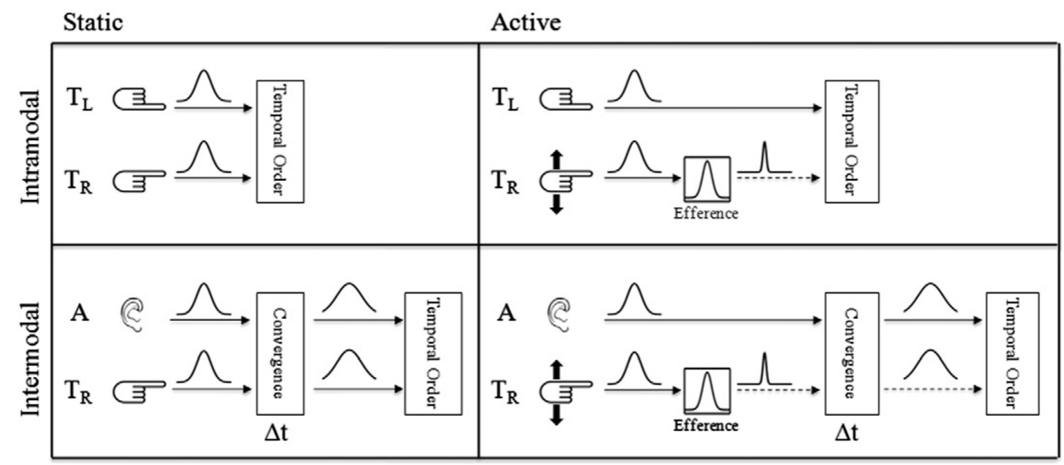

Fig. 3. A tentative model (see also paragraph 4.1). The auditory stimulus is referred to with *A*, and T_L and T_R refer to the tactile stimulus to the left and right hand, respectively. The passage of a certain amount of time is indicated with Δ*t*. The up and down arrows in the two rightmost panels indicates movement of the arm. The amount of noise in the sensory signal is illustrated by the width of the Gaussians.

movement discrimination. These findings of impaired performance during active touch are, of course, consistent with the presence of active, movement-related suppression of sensory inputs.

These first reports of impaired performance during active touch are contrary to our postulated improvement of the processing of proprioceptive signals through the use of the efference copy. However, these studies looked at spatial, not temporal perception, which presents the fascinating hypothesis that during voluntary movements, there may be a trade-off of spatial acuity in favor of temporal acuity. Although the functional purpose of such a trade-off remains unclear, the hypothesis is testable. Future experiments should be designed to measure both spatial and temporal discrimination thresholds during passive as well as active movements within the same participant.

4.2. Effect of passive arm movement on intermodal temporal alignment (PSS)

For the intermodal stimulus pairs we found that the haptic stimulus had to be presented 45 ms before the sound in order to reach subjective simultaneity. This was not a statistical fluke given that 18 out 24 of the participants exhibited this effect. Here we consider two candidate explanations for the shift.

One account is that the shift is a haptic version of the so-called flash lag effect (FLE) (Kitagawa et al., 2009). In the FLE one perceives a stationary and briefly presented visual stimulus (i.e., a flash) to lag behind a spatially aligned moving stimulus (Nijhawan, 1994). A number of explanations for the FLE have been put forward, but in essence, the phenomenon is a consequence of temporal aspects of visual processing of motion (Ichikawa & Masakura, 2006). For instance, the effect could be due to a difference in processing times of moving versus stationary stimuli (e.g., Whitney & Murakami, 1998), or to a misperception of the location of the moving stimuli (e.g., Eagleman & Sejnowski, 2000). The FLE is typically elicited with passively received visual stimuli, that is, the observer simply views the stimuli as they occur on a screen. A recent study found, however, that when the observer has a measure of control over the moving stimulus, the FLE is significantly reduced (Ichikawa & Masakura, 2006, but see Scocchia, Actis Grosso, de'Sperati, & Baud-Bovy, 2009). Moreover, the FLE is apparently not restricted to the visual system. It also occurs crossmodally between the auditory and visual modalities (Alais & Burr, 2003), and, more pertinent, there is evidence for a "motor flash-lag" effect within the visuo-motor system (Nijhawan & Kirschfeld, 2003). Observers moved their right hand which was gripping a steel rod, while during the movement, a light emitting diode was flashed at various positions relative to the unseen rod. There was a strong flash-lag effect; the flash was perceived as "centered" on the felt position of the rod was when it was, in fact, leading by about 8 cm in the direction of the movement.

From these observations we can construct a haptic analogue as follows. Let the arm movement correspond to a moving stimulus and let the haptic pulse stimulus correspond to a "flash". Since the haptic stimulus is applied to the finger, which is attached to the arm, a spatial offset between the moving stimulus and the flash is physically impossible. On the other hand, given that motion corresponds to a displacement in space over a time interval, fixing the displacement leaves only time as a degree of freedom. We can therefore speculate that the brain converts the spatial offset (which it "knows" cannot be veridical) to a temporal offset. This temporal offset manifests itself as the delayed occurrence of the haptic stimulus. Because having control over the moving stimulus reduces the FLE (Ichikawa & Masakura, 2006), the haptic FLE occurs in the passive condition but is reduced (or in present case, abolished) in the active condition. The FLE account also explains why no difference in the PSS was found between the static and active condition because the FLE requires a moving stimulus which is obviously lacking in the static condition. The FLE account is an interesting possibility that remains to be tested explicitly. However, the present study seems to provide the first evidence against it since the temporal offset was not found in the passive condition of Experiment 2.

A second account is based on the nervous system's tendency to bind actions and their effects in conscious awareness, making an action and its sensory consequences appear closer in time than they actually were (Haggard, Clark, & Kalogeras, 2002). For instance, Tsakiris and Haggard (2003) had participants voluntarily press a button with their left index finger which triggered a TMS pulse over the left motor cortex, which in turn elicited a twitch in the right hand. In separate sessions the participants reported the onset of either the action or the twitch. In yet other sessions, the button press was involuntary in that a device pressed the participant's finger on the button. The judgments were compared to a baseline in which either the action or the twitch was presented in isolation. They found that during a voluntary movement there is an attractive effect. Thus, the onset of the action was perceived to be later (on average by 26 ms) compared to baseline, while the onset of the twitch was perceived to be earlier (9 ms). Interestingly, when the movement was involuntary (i.e., passive), the opposite occurred, in which case the onset of the action was perceived to be earlier (9 ms), while the onset of the twitch was perceived to be later (15 ms). If we presume the same sensory processes for registering the twitch in Tsakiris and Haggard's experiment and the stimulus in our own experiment then we could expect a delay, which can be offset by advancing the haptic stimulus in time. This account can also explain why the shift only occurred during passive movements.

4.3. Limitations and outlook

One limitation is that the model for the JNDs does not explain the results from previous studies (see Table 1). The primary explanation for this could be the vast methodological differences between the various studies that get in the way of making any direct comparisons. In fact, it was one of the main motivations of the present study to overcome some of these differences by using a single paradigm and procedure to address a number of potentially important factors. There are, however, very likely to be a number of other potential key factors that need to be addressed.

One major factor is the means by which the haptic stimulus is generated. Indeed, each of the previous studies investigating the effects of voluntary movement on temporal perception used a qualitatively different haptic stimulus. For instance, Wenke and Haggard (2009) used electrical shocks applied to the right index and middle fingers, which were taped together. Winter et al. (2008) and Kitagawa et al. (2009) used mechanical taps to the fingers and/or lower arm. The haptic stimulus in Shi et al.'s (2008) study was delivered to the finger through a thimble on a PHANToM device, while Vogels (2004) participants held a force-feedback joystick, thus applying a force to the entire hand. Not only do all of these methods created distinct haptic stimuli, they also impose rather different constraints on the voluntary movements executed by the participants. Future research should strive to standardize the mode of haptic stimulation and limb movement.

Another factor is whether the haptic stimulus is presented to one hand or to the two hands. This might explain why Wenke and Haggard (2009) found an impairment in temporal perception during voluntary movements, while we obtained the opposite result. Whereas our stimuli were presented to the two index fingers of each hand, Wenke and Haggard presented the stimuli to the index and middle fingers of the right hand. Kuroki, Watanabe, Kawakami, Tachi, and Nishida (2010) demonstrated that temporal perception is highly dependent on the somatopic organization of the stimulation (as opposed to the position of the hands in space, or spatiotopic). For instance, they found that JNDs in a TOJ task increased by as much as 50% when electrical stimuli were presented to the index and middle finger of one hand (50 ms) in comparison to when stimuli were presented between hands (33 ms). Given this difference in temporal processes we qualify our conclusions, for the time being, to be valid to inter-manual conditions only.

Our haptic stimuli were produced at random instants during movement, which simulated the everyday behavior of exploring an unknown surface and suddenly hitting a salient feature on that surface. This was considerably different from, for instance, Kitagawa et al.'s (2009) procedure in which the haptic stimulus was generated as a result of the finger movement. Although more natural, the latter procedure creates a potential confound. Improvement in performance, as the authors argued, can be attributed to the contribution of motor command information. However, as we have already observed, it can also be argued that the improved performance was due to being better able to predict the onset of the haptic stimulus. The objective of our manipulation was to reduce the apparent causality between motor efference and sensory afference and thereby reducing the predictability of the stimuli. However, because the haptic stimulus was applied in the direction orthogonal to the movement it introduced an unnatural feature. Thus, in a sense the stimulus was incidental to the movement making it more akin to static touch. It remains an open question whether, or to what extent, the incidental nature of the stimulus changes the effect of voluntary movement on temporal haptic perception.

Finally, it has been suggested that the auditory–haptic stimulus presentation is somewhat restrictive because the auditory and haptic stimuli are presented from two distinct spatial locations, which could have affected performance. However, interestingly, the spatial separation is generally found to be advantageous to crossmodal temporal discrimination (Vroomen & Keetels, 2010). Applied to our case, spatially collocated stimuli would have lead to even bigger differences in the JNDs between the two experiments. Nevertheless, using headphones was a procedural necessity because it allowed us to mask extraneous sound from the Pantograph and to control the presentation of the auditory stimulus (see Apparatus and stimuli).

4.4. Conclusion

The haptic modality is capable of fine temporal discrimination. We found that the production of voluntary movement, as opposed to absence of movement or to involuntary movement, had a determinant effect on the participants' temporal perception acuity. Voluntary movements improved temporal processing of haptic information, which strongly suggests that the perceptual mechanisms for processing temporal information in the haptic system depend on motor command information. However, the beneficial effect was restricted to when the timing of a haptic stimulus was made with reference to another haptic stimulus. When the reference was an auditory stimulus, no significant effect of active movement was observed. Understanding the differential effects of the modality of the reference will enable us to better clarify the role of active movements in haptic temporal perception. We tentatively put forward a qualitative model that can account for these differences and proposed that additional processing noise from the crossmodal comparison counteracts the beneficial effects of the motor command information.

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