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# Speed of reaction to sensory stimulation is enhanced during movement

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ABSTRACT

We report four experiments on the speed of people's reactions to sensory stimulation while throwing and catching a basketball. Thirty participants participated in Experiment 1, split according to basketball expertise: none, intermediate (6 years on average), or advanced (20 years or more). The participants had to *catch* a bouncing basketball. The movement triggered a short tactile pulse in a tactor attached to their wrist to which they made a speeded vocal response (RT). The pulse could be presented either at rest, at two time-points during the reaching movement, or when the hand reached forward to catch the ball. The results indicated that participants responded more rapidly to vibrations on the moving hand relative to preparing or catching the ball, with expert athletes responding significantly faster than novices. In a second experiment, participants made a speeded vocal response to an auditory signal. As in Experiment 1, faster auditory RTs were observed when the hand was moving, as compared to the other time-points. In a third study, the participants responded to a pulse delivered at their resting hand at various time-points corresponding to the average timings of stimulation in Experiment 1. The results revealed comparable RTs across the tested time-points. In a final experiment, the participants made a vocal response to a pulse presented at various time-points while they were *throwing* the basketball. The results indicated faster tactile RTs while the ball was being thrown. These results are discussed with reference to the literature on goal-directed movements and in terms of current theories of attention and sensory suppression.

## 1. Introduction

Simple movements, such as a simple finger abduction (Williams & Chapman, 2002), as well as more complex goal-directed pointing or reach-to-grasp movements (Buckingham, Carey, Colino, DeGrosbois, & Binsted, 2010; Colino, Buckingham, Cheng, van Donkelaar, & Binsted, 2014; Juravle, Deubel, & Spence, 2011), are often accompanied by a reduction in what is felt, a phenomenon that researchers refer to as tactile gating, attenuation, or suppression (Chapman & Beauchamp, 2006). While the physiological and functional significance of this phenomenon still requires further experimental investigation, researchers tend to agree that it results from a combination of the descending motor command and sensory reafference (Chapman & Beauchamp, 2006; Juravle & Spence, 2011). Elegant experimental work has demonstrated that sensory suppression peaks at the onset of movement, with the movement-related detrimental effects on perceptual performance spanning a few hundred milliseconds prior to, and after, the onset of movement (Bays, Wolpert, & Flanagan, 2005). Furthermore, it appears that tactile suppression is highly dependent on the speed of movement. That is, it tends to be most apparent for those movement speeds faster than those used in tactile exploration (Cybulska-Klosowicz, Meftah, Raby, Lemieux, & Chapman, 2011; see also Juravle, McGlone, & Spence, 2013, for a commentary). Importantly, tactile suppression is modulated by response bias, suggesting that it is likely to be controlled by higher-order decision processes in the brain (Juravle & Spence, 2011, 2012.

To date, these detrimental perceptual effects have been demonstrated for those tasks where the participants have had to report the presence (Van Hulle, Juravle, Spence, Crombez, & Van Damme, 2013; Williams & Chapman, 2002), the force (Shergill, Bays, Frith, & Wolpert, 2003), or the intensity of a particular tactile stimulus (Juravle et al., 2011; Voss, Ingram, Haggard, & Wolpert, 2006; Voss, Ingram, Wolpert, & Haggard, 2008). Furthermore, although one might expect that performance in *unspeeded* discrimination and detection tasks would be similar to that seen in *speeded* tasks, it would seem as though this need not necessarily be the case. For example, we conducted a study in which participants made a speeded detection response to a tactile stimulus delivered with different probabilities to their moving or resting hand at three different timings during movement (e.g., preparation, execution, and post-movement, see Juravle et al., 2011). The results indicated a differential pattern of RTs with respect to the various phases of the goal-directed reach-to-grasp movements: Participants detected the tactile stimulus more slowly while preparing to move, as compared to while executing the movement, as well as during the post-movement period. These results made us argue in favour of there being a dissociation between

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discriminating the quality of tactile stimulation and the speed of response to tactile stimuli during movement.

This dissociation between the speed and quality of touches felt during movement found for the typical laboratory reach-to-grasp movements (Juravle et al., 2011) sparked the next series of experiments. There we were interested in investigating whether a similar distribution of tactile RTs would also be evident for other complex naturalistic goal-directed movements, such as the catching and throwing movements utilized in basketball. We have already demonstrated clear decrements in sensitivity as assessed by $d'$ while preparing and executing a (self-generated) ball-throwing movement, whereas for ball-catching movements, which are reactive by nature, only a decisional shift, as assessed by criterion $c$ response bias, was evident during movement preparation (Juravle & Spence, 2012). Here, the aim was thus to extend these findings and to test whether the speed of reaction to tactile events would also be differentially modulated over the various temporal phases of reactive versus non-reactive movements (i.e., the catches versus throws of a basketball).

In a first experiment, tactile perception was tested at different temporal phases during the execution of a ball-catching movement. It was hypothesized that a similar downward RT slope from preparation to post-movement (i.e., the catch of the ball) should be found, as in previous work on reach-to-grasp movements (Juravle et al., 2011). For this, in a first experiment of the series, the participants were instructed to catch a bouncing ball and to say 'BALL' in response to a tactile stimulus triggered at their wrist at certain hand positions during movement preparation and execution. This experiment also investigated whether long-term practice in ball-catching movements would be beneficial for what is felt during the execution of the movement. For this purpose, several groups of participants were tested, ranging from those with very limited expertise with ball games, through to those with intermediate, as well as advanced training.

## 2. Experiment 1

### 2.1. Methods

#### 2.1.1. Participants

Thirty participants (15 male, two left-handed) took part in this experiment (mean age of 25 years; age range 19–37 years). All of the participants reported normal touch, normal hearing, as well as normal or corrected to normal vision. The participants were distributed in 3 ball-expertise groups: *novices* (they had no ball experience or a very limited one from school sports), *intermediate* (played basketball or other ball sports – American football, baseball, softball, cricket, rugby, volleyball, netball – for 6 years on average), and *advanced* (participants had played basketball or baseball for 20 years on average, college 1st division or Première League athletes). The experimental session lasted for approximately 20 min and the participants received a £5 gift voucher in return for taking part.

#### 2.1.2. Apparatus

The participants had one tactor attached to their left wrist with an adjustable sports strap. The participants also had a microphone (ProSound Uni-directional Dynamic YU-33 600 Ω and 50 kΩ) attached with thread around their neck and interfaced through a custom-built voice response key connected to the main computer. Moreover, the participants had the Wii Remote attached to their left forearm with another adjustable sports strap. The Wii accelerometer (±3 g sensitivity range, 8 bits per axis, 100 Hz update rate, Lee, 2008) was interfaced through MATLAB (Psychophysics Toolbox 3; Brainard, 1997; Pelli, 1997) on Windows XP. The Wii communicated with the main computer via Bluetooth (IVT BlueSoleil v2), and the communication between the Wii Remote and Matlab was interfaced through the open source library FWIINEUR (fWIIne v0.3; http://fwiineur.blogspot.com/, downloaded in July 2009). A commercially available men's basketball (Adidas; approximately 24 cm in diameter) was used.

#### 2.1.3. Procedure

In each trial, the participants were instructed to stand with their arms at their sides. The experimenter (the same for all participants) was located approximately 2.7 m in front of the participant, with the basketball in her hands, ready to throw. An auditory signal (800 Hz, 100 ms), that participants could also hear, instructed the experimenter to throw the ball toward the participant. The experimenter ensured that the ball always bounced approximately 1.0–1.2 m in front of the participant. When the ball arrived in their vicinity, the participants reached for it and the movement of their hand triggered a 100 ms vibratory pulse to which they were instructed to give a speeded vocal response by saying the word 'BALL'. The short vibration was delivered at one of four hand positions: in the *preparation* period of the movement, at two points in time during *movement execution* (i.e., first, when the hand formed an angle of 25° with respect to the body, and second, at an angle of 45° with respect to the body), and lastly, at the *catch* of the ball when the hand reached forward and formed a straight angle with the body. The experimental script waited for 2 s for the participants to make a response after which it asked the experimenter to confirm that the current trial has come to an end. The experiment went on to the next trial once the experimenter pressed a key on the keyboard. At the end of the experiment, the participants filled in a short questionnaire concerning their athletic expertise (see Swann, Moran, & Piggott, 2015, for a recent classification of athletic expertise).

#### 2.1.4. Design

Basketball expertise was manipulated as a between-participants factor, resulting in three experimental groups: novice, intermediate, and advanced athletes. For each of the participants, the experiment consisted of 160 trials. The manipulated variable was the Timing of tactile stimulation delivery: 40 trials were performed for each of the four timings (preparation, early movement execution, mid-movement execution, and catch). The order of the trials was randomized across trials and participants.

#### 2.1.5. Data analysis

Outliers in the RTs were excluded by using the $z$-score > 3 rule (Pukelsheim, 1994), such that RT analysis was conducted on only the correct trials where the participants made a vocal response to the tactile stimulus. This operation led to a rejection of 104 trials (2.2%) of the data. The remaining data were analysed with a mixed factorial ANOVA with a within-participants factor of Timing of tactile stimulation delivery (preparation, early movement execution, middle movement execution, and catch), and the between-participants factor of Expertise (basketball novices, intermediate, or experts). Mauchly's test of sphericity was used to ensure that the data did not violate the sphericity assumption. In case of a violation being detected, the Greenhouse–Geisser correction was applied to correct the degrees of freedom; the sphericity violation is reported with $\varepsilon$ throughout text. Partial $\eta^2$ is reported as an effect size estimate for the ANOVA results.

### 2.2. Results

The results indicated a main effect of the Timing of tactile stimulation delivery [$F(3,81) = 27.83$, $\varepsilon = .615$, $p < .001$, $\eta^2_p = .508$], with participants responding more rapidly to the tactile stimulus when this was delivered to the moving hand during both execution periods, as compared to the preparation and ball-catching periods (all $ps < .001$). RTs were comparable for the preparation and ball-catching phases, as well as between the two early and mid-movement execution periods (all $ps$ = n.s.).

Moreover, a main effect of Expertise [$F(1,27) = 9.56$, $p = .001$, $\eta^2_p = .415$] was found, with novices being significantly slower than both intermediate ($p = .015$) and advanced athletes ($p = .001$). RTs were comparable for the intermediate and advanced athletes ($p = .748$). There was no interaction between Timing and Expertise [$F(3,81) < 1$, $p =$ n.s., $\eta^2_p = .027$]; see Fig. 1.

### 2.3. Discussion

One prediction for Experiment 1 was that expertise in athletic tasks would influence the speed of reaction to tactile events during movement. This hypothesis was confirmed: Novices responded more slowly than both intermediate and expert athletes, thus providing evidence for a significant advantage of expertise in athletic tasks (Aglioti, Cesari, Romani, & Urgesi, 2008; Loffing, Hagemann, Schorer, & Baker, 2015; Yarrow, Brown, & Krakauer, 2009). This result is unsurprising, considering that early in their training basketball players are taught to request the ball from their teammates simply by saying 'BALL'. It has also been demonstrated that athletes make more efficient use of visual information during action anticipation as well as during the early stages of action execution, when compared to novices (Oudejans, Van De Langenberg, & Hutter, 2002; Wu et al., 2013). Moreover, it seems that a successful catch requires the availability of visual information at the time of the ball's release from the thrower's side (López-Moliner, Brenner, Louw, & Smeets, 2010). However, although faster than novices, intermediate, and expert athletes exhibited the same pattern of RTs in Experiment 1 for the different timings of stimulation delivery during movement.

Following on from this, the main prediction for Experiment 1 was that a differential pattern of RTs would be observed for the various tested temporal phases during the externally-generated movement at which sensory stimulation was delivered. This hypothesis was confirmed: RTs were fastest during both movement execution phases, as compared to preparing and catching the ball; while no difference was observed between these last two periods.

Just to consider the preparation period, the present results mirror those found in the preparation period of self-initiated goal-directed reaches (Juravle et al., 2011). A possible explanation could be related to the fact that the descending motor command (or, more specifically, the efference copy), exerts a disruption on the somatosensory cortices (see London & Miller, 2013), thus explaining the observed slowing in RTs during the preparation period. Similarly to the goal-directed reaches investigated in laboratory-like tasks (Juravle et al., 2011), the movement execution period highlighted significantly faster RTs to tactile stimulation. Given that sensory suppression is known to appear in a moving limb (Buckingham et al., 2010; Juravle et al., 2011), the faster RTs documented during the movement execution period of this experiment further strengthen the possible demarcation between *speed* and *quality* in the tactile domain (Juravle et al., 2011).

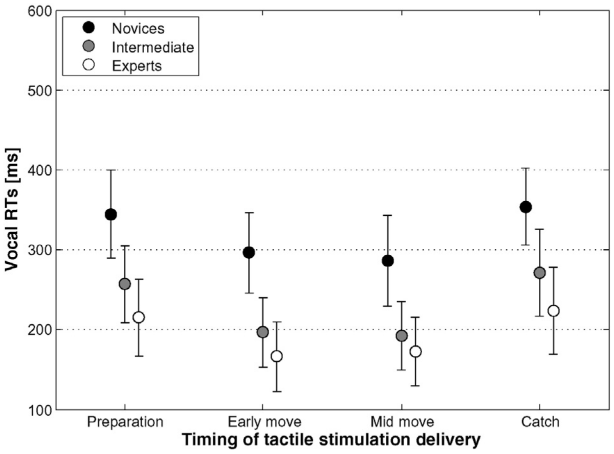

**Fig. 1.** Mean tactile RTs for the three basketball Expertise groups in Experiment 1. Vertical error bars represent 95% confidence intervals.

However, if the pattern of results reported for basic reach-to-grasp movements highlighted even faster RTs in the post-movement period (Juravle et al., 2011), for the reactive movements of catching the ball investigated here, RTs were significantly slower, as compared to movement execution. One explanation for this effect could be the fact that the peripheral feedback from the ball touching the hand interfered with the concomitant tactile stimulation presented there (see Juravle & Spence, 2011, for the demonstration of intramodal tactile interference). Any such intramodal interference could have resulted in diminished tactile sensitivity, which, in turn, may have slowed down the responses to tactile events at the time of catching the ball.

To test this hypothesis, the participants in Experiment 2 performed the same ball-catching task, however, now they made a vocal response to an auditory event that was presented over headphones. It was hypothesized that if intramodal tactile interference were responsible for the slowing of RTs at the catch of the ball, then RTs should be faster for auditory stimuli presented at the same timing during the externally-generated hand movement. However, if a more general attentional effect (e.g., a visual *looming* effect elicited by the approach of the ball, see Canzoneri, Magosso, & Serino, 2012; Franconeri & Simons, 2003; Hillstrom & Yantis, 1994; Makin, Holmes, Brozzoli, Rossetti, & Farnè, 2009; Makin, Brozzoli, Cardinali, Holmes, & Farnè, 2014, for other looming demonstrations) were responsible for the slowing of RTs at the catch, then RTs should be comparable for tactile and auditory stimuli delivered at the catch of the ball. Since, in Experiment 1, all basketball expertise groups exhibited a similar pattern of tactile RTs for the different timings of stimulation delivery, in Experiment 2 only novice athletes were tested.

## 3. Experiment 2

### 3.1. Methods

The methods of Experiment 2 were very similar to those of Experiment 1. Therefore, only the methodological differences are highlighted here. Nine participants (4 male, all right-handed; mean age of 25 years; age range 20–28 years) took part in this experiment. As mentioned already, the participants were instructed to catch a bouncing ball and to respond to an auditory signal, delivered over headphones. The *z*-score > 3 rule led to an exclusion of 32 trials (2.2%) of the total number of data points. The remaining data were analysed with paired-samples t-tests. The Holm–Bonferroni correction was used to correct for the familywise error, with all effects reported at [.0125, .0167, .0250, .05] significance levels (Holm, 1979). In a following step, we also conducted a repeated measures mixed ANOVA on the mean RT data from the novices with the within-participants factor of Timing of sensory stimulation delivery (preparation, early movement execution, middle movement execution, and catch), and the between-participants factor of Experiment (1 vs. 2).

### 3.2. Results

The results indicated that participants responded significantly more rapidly to the auditory stimulus when this was delivered during the early execution period of the movement, as compared to both the preparation period ($t(8) = 3.18$, $p_{one\text{-}tailed} = .0065$, $r = .885$), and at the catch of the ball ($t(8) = 3.63$, $p_{one\text{-}tailed} = .0035$, $r = .864$). Similarly, RTs to the auditory stimulus were faster when this was delivered mid-movement relative to the catch of the ball ($t(8) = 3.73$, $p_{one\text{-}tailed} = .0030$, $r = .882$), as well as relative to the preparation period ($t(8) = 2.57$, $p_{one\text{-}tailed} = .0165$, $r = .885$).

When comparing the novice data from Experiments 1 and 2, a significant main effect of Timing of sensory stimulation delivery was found [$F(3,51) = 14.90$, $p < .001$, $\varepsilon = .485$, $\eta^2_p = .467$]. This result highlighted the previously observed difference between the different timings of stimulation delivery: Namely, the RTs in the execution period were faster than those recorded during both the preparation and ball-catching periods (all *ps* < .013). By contrast, no significant difference was found between RTs in the preparation and ball-catching periods, nor between the two movement execution periods (all *ps* = n.s.). Furthermore, the main effect of Experiment failed to reach significance [$F(1,17) = 4.10, p = .059, \eta^2_p = .194$]. There was no significant interaction between the two variables of Timing of stimulation delivery and Experiment [$F(3,51) = 1.08, p = .365, \eta^2_p = .060$]. See Fig. 2 for a depiction of the novice RT data from the two experiments.

### 3.3. Discussion

Experiment 2 was designed to investigate a possible explanatory factor for the distribution of tactile RTs that had been obtained in Experiment 1: faster RTs while moving, as opposed to the RTs found during both preparing and ball-catching. The results highlighted a comparable distribution of RTs in the tested novice groups for the different temporal phases of the movement when sensory stimulation was delivered in Experiments 1 and 2.

Such results could signal that the slower RTs registered at the catch of the ball for both the tactile and auditory stimuli provide an indication of attentional capture, or an attentional looming effect, associated with the approach of the ball (Canzoneri et al., 2012; Franconeri & Simons, 2003; Hillstrom & Yantis, 1994; Makin et al., 2009, 2014). A related explanatory factor for the similar RTs registered during the various tested phases of the movement for both tactile and auditory stimuli could be intersensory facilitation: That is, the response to a sensory stimulus (i.e., the tactile vibration or the auditory beep) is shortened if this is presented at about the same time as another stimulus (i.e., the ball, in the experiments reported here), an effect explained by the principle of energy summation (e.g., Morrell, 1967; Nickerson, 1973).

Alternatively, however, another factor that could account for the slowing of RTs at the time of the catch of the ball could be a simple dual-task effect: At the time of the catch, the participants had to perform an additional action that followed on from the goal-directed reaching for the ball, the actual act of *catching* the ball. In order to test this question, Experiment 3 was designed so that participants responded vocally to a tactile stimulus delivered while at rest. This could be delivered at one of four different points in time after the initiation of the trial. The time points were derived by averaging the timings of tactile stimulation delivery from Experiment 1 (i.e., motor preparation, early movement execution, mid movement execution, and ball-catching). It was hypothesized that if a dual-task effect was responsible for the slower RTs observed at the time of the ball-catch, then in the absence of movement this effect should be absent (i.e., no difference in RTs should be observed as a function of the timing of stimulation delivery). At the same time, if a difference in the tactile RTs for the different timings of stimulation used in Experiment 3 were to be found, then other attentional factors (e.g., the well-known phenomenon of inhibition of return, Klein, 2000; Lupianez, Klein, & Bartolomeo, 2006; Spence, 2010; Spence, Lloyd, McGlone, Nicholls, & Driver, 2000) could be taken to account for a temporal dissociation in the speed of reporting tactile events.

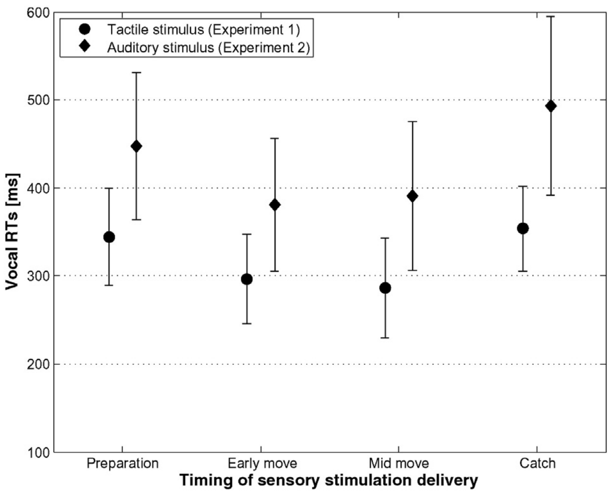

**Fig. 2.** Mean sensory RTs for the novice data in Experiments 1 and 2. Vertical error bars represent 95% confidence intervals.

## 4. Experiment 3

### 4.1. Methods

Since the methods of this experiment are very similar to those used in Experiments 1 and 2, only the differences are highlighted. Ten participants (4 male, all right-handed; mean age of 22 years; age range 19–28 years) took part. They made a response while standing to a tactile stimulus delivered to their wrist. Participants did not move their hands for the duration of the trial. The experiment consisted of 100 trials, with 25 trials for each averaged timing of stimulation from Experiment 1 (1010 ms, 1590 ms, 1760 ms, and 2210 ms after the beginning of the trial). The *z*-score > 3 rule led to an exclusion of 38 trials (4%) of the total number of data points. The remaining data were analysed using Holm–Bonferroni-corrected paired-samples *t*-tests with the effects reported at [.0125, .0167, .0250, .05] significance levels. We also conducted one additional repeated measures mixed ANOVA with the within-participants factor of Timing of tactile stimulation delivery (preparation, early movement execution, middle movement execution, and catch), and the between-participants factor of Experiment (1 vs. 3).

### 4.2. Results

The results indicated that in the absence of movement, the timing of stimulation delivery did not influence tactile RTs (all $ps_{one\text{-}tailed} > .0285$). When comparing the novice RT data between Experiments 1 and 3, the results highlighted a significant main effect of Timing [$F(3,54) = 5.46, \varepsilon = 736, p = .006, \eta^2_p = .233$], an effect resulting from RTs in the preparation period being significantly slower as compared to both early ($p = .019$) and mid-execution periods ($p = .030$). There was no main effect of Experiment [$F(1,18) = .670, p = .424, \eta^2_p = .036$]. Lastly, we found an interaction between the two variables of Timing and Experiment [$F(3,54) = 3.82, p = .027, \eta^2_p = .175$]. However, all of the post hoc comparisons of interest for each of the timings of stimulation between the two experiments proved non-significant (all *ps* > .166). See Fig. 3 for a depiction of the RT data from the novices in Experiment 3.

### 4.3. Discussion

The goal of Experiment 3 was to test whether a dual-task effect would be responsible for the slowing of RTs at the catch of the ball that was seen in Experiment 1. In the absence of movement, the results nevertheless highlighted comparable RTs for all the timings of tactile stimulus delivery. Such a result can be taken to suggest that movement acts as a distraction on our participants' performance for the perceptual speeded response task. It could therefore be argued that the slowing of RTs observed in both the preparatory and catch phases of Experiments 1 and 2 are a direct result of the movement.

To summarize the findings of the three experiments reported so far, it appears as though the execution period of the movement favours speeded responses to sensory stimuli (e.g., tactile stimulation in Experiment 1, and auditory stimulation in Experiment 2). Moreover, the preparation period indicates a significant slowing of RTs for both types of sensory stimuli tested in Experiments 1 and 2. Such an effect is most likely the result of the disrupting descending motor command on perceptual performance (see Juravle & Spence, 2012, for a discussion). Importantly, the timing of the catch of the ball results in the

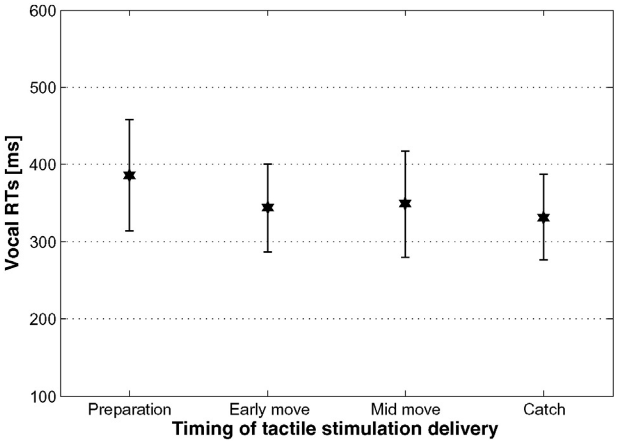

**Fig. 3.** Mean tactile RTs for the novice data in Experiment 3. Note that in this experiment there was no movement performed; the captions on the abscissa were so-chosen to match the other figures. Vertical error bars represent 95% confidence intervals.

slower processing of sensory stimuli delivered to the movement effector. Possible explanations for this effect are: *i*) movement itself acts as a distraction on the processing of incoming sensory stimuli, hypothesis already tested in Experiment 3 (see also Juravle & Spence, 2011), and *ii*) the approaching ball exerts a looming effect, or captures the participant's attention, a hypothesis that was tested in Experiment 2.

In a next step, in order to further test hypothesis *ii*), an investigation was carried out to test whether this slowing of RTs to sensory stimulation would generalize across different types of movement. For this, in Experiment 4, self-initiated goal-directed movements were tested over the same timescale. That is, this time the participants had to throw the ball to the experimenter and RTs were recorded for tactile stimuli delivered at different points in time during the goal-directed movement: the preparation of the throw, movement execution, and the release of the ball. It was hypothesized that if externally-generated and self-initiated movements affected tactile perception in a similar manner, then a similar pattern of RTs should be found for the self-initiated movements, as for their externally-generated counterpart. However, if different processes act on tactile perception during the preparation and execution of the two types of movement, then a difference in tactile RTs will be observed between self- and externally-generated movements. Note that as opposed to the externally-generated movements tested in Experiments 1–2, an attentional ball-looming effect could not account for the slowing of responses that could potentially be found at the time of the throw. Such an explanation is unlikely because the ball leaves peripersonal space, and thus could not be treated as incoming sensory stimulation.

## 5. Experiment 4

### 5.1. Methods

The methods of Experiment 4 were similar to those of Experiment 1. Therefore, only the methodological differences will be highlighted here. Ten participants (2 males, one left-handed; mean age of 25 years; age range 22–31 years) took part in this experiment.

A first auditory signal (*prepare signal*, 100 ms, 400 Hz) instructed the participants to prepare to throw the ball to the experimenter. A second auditory signal (100 ms, 800 Hz), delivered 1100 ms later, acted as the *go signal* to initiate the throwing movement. Tactile stimulation was delivered to the participants' wrist at different points in time during the movement: in the preparation period (500 ms after the prepare signal), early execution period (immediately after the go signal), mid-movement execution (100 ms after the go signal), or at the release of the ball (200 ms after the go signal). Note that in Experiments 1 and 2, the experimenter always bounced the ball on the floor (in approximately the same location), so that it arrived at the participant's hand from roughly the same angle. For this reason, the bouncing of the ball was used in Experiment 4, when the participant threw the ball in the direction of the experimenter.

The *z*-score > 3 rule led to an exclusion of 39 trials (2.4%) of the total number of data points. The remaining data were analysed using Holm-Bonferroni corrected paired-samples t-tests with the effects reported at [.0125, .0167, .0250, .05]. An additional repeated-measures mixed ANOVA was conducted on the mean tactile RTs with the within-participants factor of Timing of stimulus delivery (movement preparation, movement execution, and ball catching or throwing), and the between-participants factor Experiment (1 vs. 4).

### 5.2. Results

The results indicated that participants were significantly slower to respond to the tactile stimulus when this was delivered during the preparation period of the movement, as compared to both the early ($t(9) = 3.48$, $p_{one\text{-}tailed} = .0035$, $r = .369$) and mid-execution periods ($t(9) = 4.43$, $p_{one\text{-}tailed} = .001$, $r = .433$). Furthermore, RTs were also slower during early movement execution as compared to the throw of the ball ($t(9) = 2.63$, $p_{one\text{-}tailed} = .0135$, $r = .825$), however, the RTs were comparable between the mid-movement and throw periods ($t(9) = 1.48$, $p_{one\text{-}tailed} = .0635$, $r = .855$).

When comparing the novice data from Experiments 1 and 4, a significant main effect of the Timing of tactile stimulation delivery was observed [$F(3,54) = 12.37$, $p < .001$, $\varepsilon = .637$, $\eta^2_p = .407$]. Pairwise comparisons indicated that the preparation period was slower than the early execution ($p = .002$), mid-execution ($p = .001$), and ball-catching or throwing periods ($p = .002$); all other comparisons were non-significant (all *ps* > .334). Furthermore, no significant main effect of Experiment was found [$F(1,18) < 1$; $p =$ n.s., $\eta^2_p = .016$]. Nevertheless, a significant interaction between the two variables of Timing of stimulus delivery and Experiment was observed [$F(3,54) = 7.49$, $p < .001$, $\eta^2_p = .294$]. Pairwise comparisons indicated that the mean RTs registered in Experiment 1 at the catch of the ball were significantly slower than the mean RTs recorded at the throw of the ball in Experiment 4 ($p = .035$). See Fig. 4 for a depiction of the novice tactile RT data from the two experiments.

### 5.3. Discussion

Experiment 4 highlighted faster RTs at the time of the throwing of the ball. Furthermore, when comparing the data from Experiments 1 and 4, a clear difference in tactile RTs was observed with respect to the type of movement that was executed: The throw of the ball yielded significantly faster RTs to tactile stimulation, as compared to the catch of

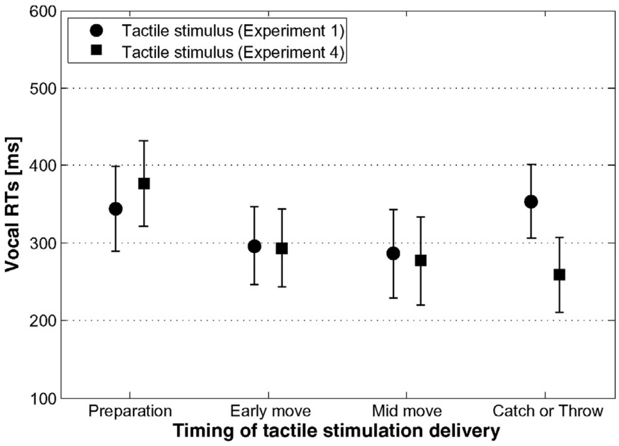

**Fig. 4.** Mean tactile RTs for the novice data in Experiments 1 and 4. Vertical error bars represent 95% confidence intervals.

the ball. These results complement existing sensitivity data on externally-versus self-generated movements: That is, we feel less when we prepare to throw a ball, as compared to simply preparing to catch it, whereas for both movements we certainly feel less during movement execution than while at rest (Juravle & Spence, 2012). The finding of faster RTs at the time of the throwing of the ball in Experiment 4 thus suggests a potential parallel processing of sensory information during movement, an interpretation that will be further explored in the General discussion section.

## 6. General discussion

The results of the present study provide evidence in favour of a differential distribution of sensory RTs with respect to the various temporal phases of catching and throwing movements of a basketball. First of all, these data indicate that the speed of reaction to sensory events is significantly faster when these are delivered during the execution period of the movement, as compared to the preparation and catch of the ball. A possible explanation for this effect relates to the distinction between speed and quality in the tactile domain during movement (Juravle et al., 2011). As such, the enhanced RTs to sensory stimulation would appear to support an explanation of the data that is based on a supramodal attentional-control mechanism influencing the organism (e.g., see the work on crossmodal attention; Spence & Driver, 1996, 2004). That is, a control system operating across sensory modalities, as opposed to a modality-based attention-directing one could be taken to explain the RT data that has been reported here (Farah, Wong, Monheit, & Morrow, 1989). Particularly with regard to the present data, *attention* could be taken to account for signalling a change in the current state of the body and/or the environment, with this effect taking place preferentially during movement execution.

Furthermore, when opposing the faster RTs at the time of the throw in Experiment 4 to those recorded at the time of the catch in Experiment 1, a potential explanatory factor could be *attentional capture*: That is, incoming *objects* (i.e., the basketball) entering our peripersonal space are prone to spark an attention-capture mechanism in the tactile domain and lead to a slowing of RTs at the timing of the catch of the ball. The attention capture explanation is also supported by the RTs recorded in response to tactile stimulation delivered during the reach-to-grasp movement execution in a laboratory setting: RTs in the post-movement period, once the grasp of the goal object has taken place, are faster than during the execution period (Juravle et al., 2011). Furthermore, it has recently been suggested that the enhancement effect of the visual looming stimuli on tactile events stems from a defensive mechanism, that is, we inherently perceive approaching objects as more dangerous, as compared to objects leaving our personal space (Clery, Guipponi, Odouard, Wardak, & Ben Hamed, 2015; Kandula, Hofman, & Dijkerman, 2015). Importantly, the attention-capture-like effect found in this study also supports the multisensory thesis concerning looming stimuli (Cappe, Thut, Romei, & Murray, 2009), since the ball arrival carries not only visual information, but also auditory information.

A similar effect to the catches in Experiment 1 was evident in Experiment 4 with faster reactions being observed in response to tactile events at the time of the throwing of the ball, as opposed to movement execution. Interestingly, what throwing actions (as utilized here) and grasping actions (from previous experiments in our lab) have in common is the already-ended manipulation of the goal object. While reaching out to catch the ball, our attention is rightfully captured by the object that is approaching us. In this respect, an interesting future avenue for research could be concerned with the physical parcellation of peripersonal, and also even more distant spaces, in order to further characterize the mechanisms governing sensorimotor interactions (see Van der Stoep, Nijboer, Van der Stigchel, & Spence, 2015, for a recent review).

As an alternative to the incoming objects capturing attention account, the *actor* (i.e., the participant) could be monitoring the experimenter's action and be differentially biased in responding to the presence of tactile events during the preparation and execution of simple ball-catches or throws. Indeed, when the participants in one of our earlier studies were given a tactile perceptual task at the time when the ball had to be caught, a significantly altered response bias was observed. That is, our participants were more inclined to report a change in the tactile stimulation delivered at their wrist when this occurred as the ball was approaching them and they were preparing to catch it, as opposed to conditions of rest and ball-throwing (see Juravle & Spence, 2012). Here, another possible mechanism that could be taken to explain our findings relates to the well-known phenomenon of time compression during voluntary action. For example, studies investigating temporal precision for sensory events during the execution of voluntary movement report both improvement and deterioration in temporal precision when these sensory stimuli closely follow the executed action (Frissen, Ziat, Campion, Hayward, & Guastavino, 2012; Wenke & Haggard, 2009; see also Winter, Harrar, Gozdzik, & Harris, 2008). It has been suggested that the execution of a voluntary action temporally *attracts* the sensory event (i.e., the experienced sensory consequence of the action) toward the action itself (Haggard, Clark, & Kalogeras, 2002). With this consideration in mind, the enhanced speed of responding to sensory events, as reported in the present study during the execution of the goal-directed action, could be taken to signal that the sensory events are perceived as occurring earlier. This alternative explanation could particularly support the faster speed of reaction at the time of the throwing of the ball as opposed to its catch that we find, particularly since throwing could be taken as a more self-determined action relative to the catch of the ball.

Having obtained an enhancement of tactile information processing during the execution period of a naturalistic movement such the catch or throw of a basketball brings into the discussion the exact perceptual task that our participants were required to perform. In previous experiments tactile performance has mostly been measured while the upper or lower limbs were executing the movement. Here, by contrast, we measured vocal RTs. Because movement characterizes sensory suppression, vocal responding, we assume, will supposedly be protected from the effects of tactile suppression. Indeed, our results are in line with previous foot RT data that has indicated faster responses to sensory events while executing the movement, as opposed to its preparation (Juravle et al., 2011). As such, these similar results of faster speed of reaction to tactile events during movement measured at different effectors make us argue in favour of a parallel process that takes place at the time sensory suppression is exerting its influence on the moving organism. This process appears very similar to the preparedness for action that has classically been attributed to attention (Rizzolatti & Craighero, 2010; Rizzolatti, Riggio, & Sheliga, 1994).

To acknowledge the implications of the findings detailed in this study, just consider the design of tactile warning signals in the human factors industry, ergonomics, industrial design, or sports science. These warning signals need to be delivered to the skin during the execution of various goal-directed movements (e.g., in designing training programmes in team sports such as cricket where especially tight eye-hand coordination is required — tactile cues delivered during movement execution could inform the athlete of concurrent developments on the field to which (s)he has no access at the specific movement time). Furthermore, consider the recent explosion of wearable technology, particularly physiological-monitoring bracelets. They all seem to involve some form of vibration. In order to enhance their chances of success in the marketplace, their developers will need to acknowledge that tactile information is differentially processed during the execution period of goal-directed movement (i.e., quality of tactile sensation is attenuated, whereas we are very fast to detect incoming stimuli on our receptors). Therefore, research such as the experiments reported here and previously in our lab would lead to the suggestion that manufacturers should deliver touches that the user only needs *to detect* during movement – Specifically, only deliver stimulation such as for example, at most a present/absent or yes/no warning-type-of-message, and not necessarily a message where the user needs to extract meaning from (e.g., the wearable tactor belts might not be the ideal candidates as far as goal-directed movement is concerned).

## 7. Conclusions

In summary, the experiments reported here demonstrate that the cognitive system readily responds to incoming sensory stimulation while moving, with the speeded responses directed by a supramodal control system seemingly at stake during movement execution. The looming basketball captures attention within the two sensory modalities tested here at the time of ball-catching. By contrast, while executing ball-throwing actions we are faster to respond to sensory events and less likely to be affected by attention capture. Future research needs to further address sensorimotor contingencies within other sensory systems, as well as other diverse goal-directed movements outside the laboratory setting.

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