Tactile pre-motor attention induces sensory attenuation for sounds

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Abstract

Self-produced stimuli appear attenuated compared to stimuli generated by others. This effect is known as sensory attenuation (Blakemore et al., 1999). Here, we asked whether an attentional prioritization for the tactile modality during a goal-directed hand movement leads to sensory attenuation for sounds. We presented stimuli in a virtual reality setup that allowed to manipulate the time of tactile feedback when pressing a virtual button. We found that a tactile impulse was perceived as more intense in the moment the hand pushed the button (N = 29). In a second experiment (N = 25), participants pushed a button and estimated the intensity of sounds. We found sensory attenuation for sounds only when tactile feedback was provided at the time the movement goal was reached. These data indicate that sensory attenuation for sounds occurs because tactile attention is boosted towards the movement goal, leaving reduced attentional resources for the auditory modality.

Keywords: sensory attenuation, attention, motor planning, movement sequences, tactile discrimination

Introduction

A pivotal requirement for the successful interaction with the environment is the ability to distinguish sensory stimuli that are produced by ourselves from those that have an external cause. The plethora of examples illustrating this need ranges through the animal kingdom from the electric fish that can dissociate self-and externally produced electric fields (Bell, 2001) to humans who are not disturbed by the retinal motion that is generated by their own eye movements (Wurtz, 2018). Research into these phenomena early on demonstrated that a signal must exist which tells sensory areas that a movement is upcoming (von Holst & Mittelstaedt, 1950). In consequence, sensory areas alter their receptivity for the sensory effects produced by that movement. The ensuing attenuation of sensory events has been found for tactile (Bays et al., 2006), auditory (Weiss et al., 2011) and visual events (Cardoso-Leite et al., 2010). A comparator model account has been proposed in which the initiation of a movement triggers an efference copy that is used to build up a forward model which predicts the consequences of the movement (Blakemore et al., 2002). If the prediction and the actual sensation match, the strength of that sensation is reduced, resulting in sensory attenuation.

Here, we provide evidence that goal-directed movements like button presses induce tactile pre-motor attention shifts to the moving hand in order to prioritize processing. In consequence, processing in other sensory modalities is decreased, thus resulting in sensory attenuation. In closed-loop movement control negative feedback about the success of a movement is necessary to stop movement execution. For instance, if we press a button the tactile sensation ensuing when the finger touches the button is the signal to stop moving further. Efficient movement control thus requires that the registration of the tactile sensation at the time the hand reaches the goal object receives priority compared to other sensory event. To meet this requirement, tactile attention should shift to the touching finger shortly before the movement goal is reached. Pre-motor attention shifts are known to occur for several movements: For eye (Deubel & Schneider, 1996)- and for pointing (Baldauf et al., 2006) movements, it has been repeatedly demonstrated that visual attention shifts to the

goal location of the movement shortly before movement onset. The purpose of that shift is to predict the sensory consequences following movement termination in order to estimate movement success and - in the case of saccade eye movements - to establish visual stability across the movement (Baldauf & Deubel, 2008). A similar predictive attention shift has been found for pointing movements. Deubel and colleagues (1998) demonstrated that for the preparation of a pointing movement to a certain location, the perceptual processing is partially initiated even before movement onset. Similarly, to the attention effects observed at the time of saccades, discrimination performance presented close to the goal object of a pointing movement was higher than when presented at other locations. Other studies have tested tactile attention shifts around the time of movement preparation, execution and after movement termination (Juravle et al., 2010). They found that tactile sensitivity in the phase after the movement is significantly lower compared to the execution phase of the movement.

Response amplification is a common feature of selective attention shifts (Desimone & Duncan, 1995; Posner & Dehaene, 1994; Posner & Petersen, 1990). Consequently, if processing of tactile sensations is prioritized at the time the hand touches the object, tactile sensitivity should be increased. This boost of tactile attention at the time when reaching the movement goal might limit attentional resources in the remaining modalities. Transfer of attentional resources between the tactile and the auditory modality is especially likely given for their functional connectivity. The human somatosensory cortex co-activates with auditory cortex during the processing of vibrations and texture (Butler et al., 2012; Iguchi et al., 2007; Nordmark et al., 2012; Schürmann et al., 2006). Convento and colleagues (2018) demonstrated that participants were impaired in an auditory frequency discrimination task when they received TMS stimulation over S1 and attended to tactile frequency information. An influence of attention on these two cortical systems was already described by Gescheider et al. (1975). When auditory and tactile stimuli were presented individually or simultaneously, the cognitive processing was only impaired for the concurrently occurring stimuli. Thus, the distribution of attention was an important determinant of performance.

We tested this hypothesis by asking two major questions: First, do tactile stimuli appear as more intense at the time the hand makes contact with the button than at the beginning of the movement? It is long known that during arm-movements, tactile gating is responsible for decreased tactile thresholds while the movement is ongoing (Chapman et al., 1987). Juravle et al. (2010) tested tactile thresholds while participants had to grasp a computer mouse. They found that tactile sensitivity in the phase after the movement is significantly lower compared to the execution phase of the movement. The threshold values rise from preparation to execution and decrease again from execution to the phase after the movement (Juravle et al., 2010). We tested tactile thresholds during closed-loop button-press movements that are commonly used to measure sensory attenuation of external events (Weiss et al., 2011). Second, does attention processing the tactile sensation during a button press determine attenuation for sounds that are contingent on the button press?

We investigated these questions in a virtual reality setup that allowed to manipulate the time of the tactile feedback when pressing a button. A virtual button was presented in a head-mounted display and tactile feedback was provided via mini vibrators that were attached to the participants index fingers. In Experiment 1, we tested perceived vibration intensity at three different movement times. In Experiment 2, we sought to find out whether the presence of tactile feedback determines sensory attenuation of actively produced sounds.

Methods

Participants

A total of 30 study participants took part in Experiment 1 (including one author). For one participant psychometric functions could not be estimated, indicating that the task was not performed correctly. Therefore, the final sample in Experiment 1 consisted of 29 right-handed participants with unrestricted vision or vision correction (age: 18 - 56 years [M_{age} = 26.52, *SD* = 9.87], sex: 11 male, 17 female, 1 diverse).

In Experiment 2 25 right-handed participants with unrestricted vision or vision correction took part (age: 19 - 36 years [M_{age} = 24.03, *SD* = 3.38], sex: 6 male, 19 female).

Participants were recruited in the University Düsseldorf or via social networks. Experiments were approved by the local ethics committee of the Faculty of Mathematics and Natural Sciences of Heinrich Heine University, Düsseldorf (identification number: 757184), and are in accordance with the Declaration of Helsinki. Handedness was assessed using the Edinburgh Handedness Inventory and all participants were classified as right-handers. Participants were compensated with participation hours or remunerated by means of an expense allowance. Informed consent was obtained from all participants.

Since there is no precisely matching study that describes sensory attenuation effects for sounds in motor demand in VR the sample sizes were based on similar studies concerning the effects of motor involvement, both increasing and decreasing the response to a target stimulus as shown in our paradigm. Here the number of test subjects varied approximately between 24 - 30 subjects (Guo & Song, 2019; Klaffehn et al., 2019; Miall et al., 2006; Timm et al., 2014) leading to our sample size of 30 and 25 participants in Experiment 1 and 2.

General materials

The Experiments took place in the same setting with only minimal adjustments. Participants in the experiments were asked to press a button in virtual reality environment, presented to the participants through VR goggles (Oculus Rift Development Kit 2). VR goggles included a horizontal and vertical field of view of 100° and a refresh rate of 60 Hz. In the head mounted display, participants saw a blue/green virtual button in front of a dark background. Hand movement of participants was captured with a motion sensor (Leap Motion, Orion V 2.3.1+31549 sampling at 60 Hz with a field of view of 140 x 120°). A virtual hand model was shown that moved synchronously with the real hand. Vibrotactile stimuli were presented via mini-vibrators that were attached to the right index fingers of the participants. The vibrotactile stimuli were controlled by an Arduino Nano microcontroller

ATmega328 operating at 5 Volt. Participants responded on a foot pedal (UPC ECS-PPD-F) placed under the table. The experiments were run on a MacBook Pro (Retina, 15-inch, 2015).

Procedure in Experiment 1

In Experiment 1, participants had to perform a goal-directed hand movement to press the virtual button with their right hand. In each trial they made an arm movement starting with the right hand and forearm held up and moved downwards to press the button (see Figure 1). The virtual button went down 5° when pressed.

Each trial started with the presentation of a *"Ready"* message that was displayed on the left side of the screen center. After 500 ms, it was replaced by a *"Set"* message which was presented for 500 ms. Participants had to press the button at the corresponding *"Go"* time, i.e., 500 ms after appearance of the "*Set"* message. A vibrotactile stimulus was presented to the right index finger of the moving hand either before the start of the movement (start), during the movement (move) or when the button was pressed (press). These presentation times of the vibrotactile stimulus were randomized across trials. The vibration on the index finger of the right moving hand was constant in each trial (50% of the maximum vibration intensity of 5 Volt). After the button was pressed, a comparison vibration was delivered 700 ms later to the index finger of the resting left hand. The comparison vibration varied randomly across trials between 20-40% and 60-80% of the maximum value of 5 Volt (in 6 equidistant steps). After each trial, participants had to decide which vibration was perceived stronger by using a foot pedal. Pedal pressing was counterbalanced between participants with either pressing the right button when the first vibration felt stronger and the left button when the second vibration felt stronger or vice versa. Then, after giving an answer, the next trial started immediately. A total of 180 trials were conducted in the first session (60 trials for each of the three movement times; ten trials each for each vibration intensity of the comparison vibration per time point).

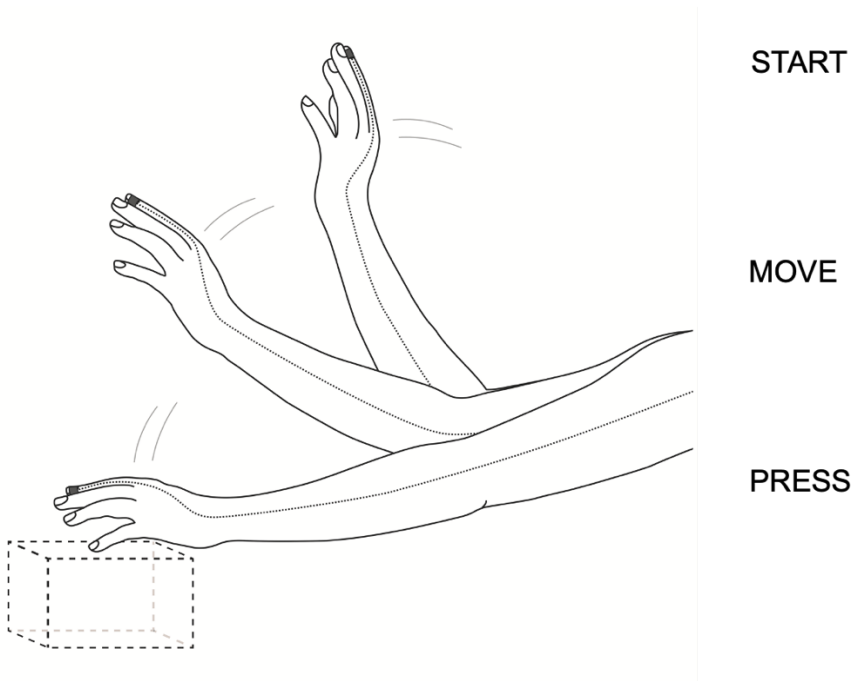

Figure 1. Experimental setup. Participants were asked to perform a goal-directed hand movement to press a virtual button. During the movement the hand starts perpendicular to the button (start), is then moved down towards the button (move) and ends the movement with a button press (press). The mini vibrators attached to the right index finger are shown as black dots and their cables as black lines. Participants experienced a tactile stimulation on the right moving index finger either during start, move or press hand movement time (Experiment 1). A comparison stimulation was delivered 700ms after the button press to the resting index finger of the left hand. The virtual button is presented with a dotted rectangular box.

Procedure in Experiment 2

Experiment 2 was divided into two conditions, called ‘no-tactile’ and 'tactile’. It was randomized whether participants first started with the ‘no-tactile’ or 'tactile’ condition. Both experimental conditions were conducted in the same virtual reality setup as Experiment 1. Again, participants were asked to perform a goal-directed movement to press the virtual button with the right hand within VR. Here, a tone (MacBook sound ‘Funk’) was presented either during the movement time of starting the movement or when pressing the button. The tone was presented with 63.3 dB (50% of maximum intensity of the MacBook) through headphones. 700 ms after finishing the goal-directed movement a comparison tone was played, either with 80 - 60% or 40 - 20% of the maximal auditive intensity (71.6, 68, 65,5, 60.4, 55.4 or 51.9 dB). Participants were asked to estimate which tone was louder by pressing either the right or left button of the foot pedal placed on the floor. It was randomized

between participants whether the first or second tone was assigned to the right side of the foot pedal. The timing of the first tone (start vs. press movement time) as well as the volume of the comparison tone (80 - 60% or 40 - 20%) was randomized. A total of 120 trials was conducted in the condition ‘no-tactile’ (60 trials for each of the two movement times; ten trials each for each auditory intensity per time point).

In the condition ‘tactile’ of Experiment 2 the main part of the test procedure remained similar to the condition ‘no-tactile’. Each trial started 500 ms after the “*Set”* message and a tone was played either before or after the goal-directed movement. However, a mini-vibrator was attached to the participants right index finger. Each time the button was pressed within VR, participants felt a vibration on the right index finger of their moving hand. More precisely, in 100% of trials in condition ‘tactile’ a stimulus was delivered to the right moving index finger during the button press. In 50% of trials a tone was played when starting the movement and in 50% of trials the tone was played when pressing the button. Headphones prevented auditory perception of the tactile stimulus.

A total of 120 trials was conducted in the condition ‘tactile’ (60 trials for each of the two movement times; ten trials each for each auditory intensity per time point). Presentation time of the stimulus and auditory intensity were randomized across trials.

Data analysis

For Experiment 1, we analyzed offline when the vibration occurred with regard to hand movement position. In total we differentiated between three hand movement phases. The first movement phase included all trials with tactile stimulations that occurred 250 ms before the go-signal, the second all trials in which tactile stimulation occurred equal to or more than 250 ms after the go-signal and the third phase all trials in which tactile stimulation occurred concurrently with the button press. For all experiments data were averaged for tactile/auditive intensities within each participant for each of the movement times. Afterwards all data were then fitted by a cumulative gaussian function. The point of subjective equality

(PSE) represents the magnitude at which the probe vibration (tactile stimulation) is perceived as stronger than the comparison vibration/tone on fifty percent of the trials. The just noticeable difference (JND) is the minimum level of stimulation that a person can detect 50 percent of the time.

To identify whether there were significant differences between the PSEs and JNDs during the three movement times in Experiment 1, a one-way repeated measures ANOVA was used. For experiment 2 we used a 2 x 2 factorial design to perform an ANOVA for repeated measures to find significant differences between the PSEs and JNDs of ‘no-tactile’ and 'tactile'.

The data that supports the finding of the study are available at: https://osf.io/edt74/.

Results

Experiment 1

In Experiment 1 a tactile stimulation on the right index finger was felt during one of the three hand movement times start, move and press. Data for the three movement times were fitted by cumulative gaussian functions individually for each participant. Psychometric functions of one exemplary participant are shown in Fig. 2. A one-way repeated measures ANOVA was conducted to identify whether the PSEs for the three hand movement times differ significantly from each other (M_{start} = 5.16, *SD* = 10.64, M_{move} = 8.73, *SD* = 8.73; M_{press}= 11.96, *SD* = 9.09). There was a statistically significant difference between all three movement times ($F(2, 56) = 8.23$, $p = .002$, $n_p^2 = .227$). A post hoc analysis (Bonferroni corrected) revealed that there was a significant difference between the start and press movement time (*MD* = 6.80, *SEM* = 2.03, 95% CI [2.63, 10.96], $p < .001$). No significance was found between start and mid movement time (*MD* = 3.57, *SEM* = 1.56, 95% CI [0.92, 7.37], $p = .113$) and between mid and press movement time (*MD* = 3.27, *SEM* = 1.37, 95% CI [-0.56, 7.715], $p = .179$).

We also analyzed JNDs with a one-way repeated measures ANOVA (M_{start}= 18.27, *SD* = 17.88; M_{move}= 12.89, *SD* = 16.45; M_{press} = 16.23, *SD* = 17.36). No significant main effect was found here ($F(2, 56) = 1.757$, $p = .182$, $n_p^2 = .059$).

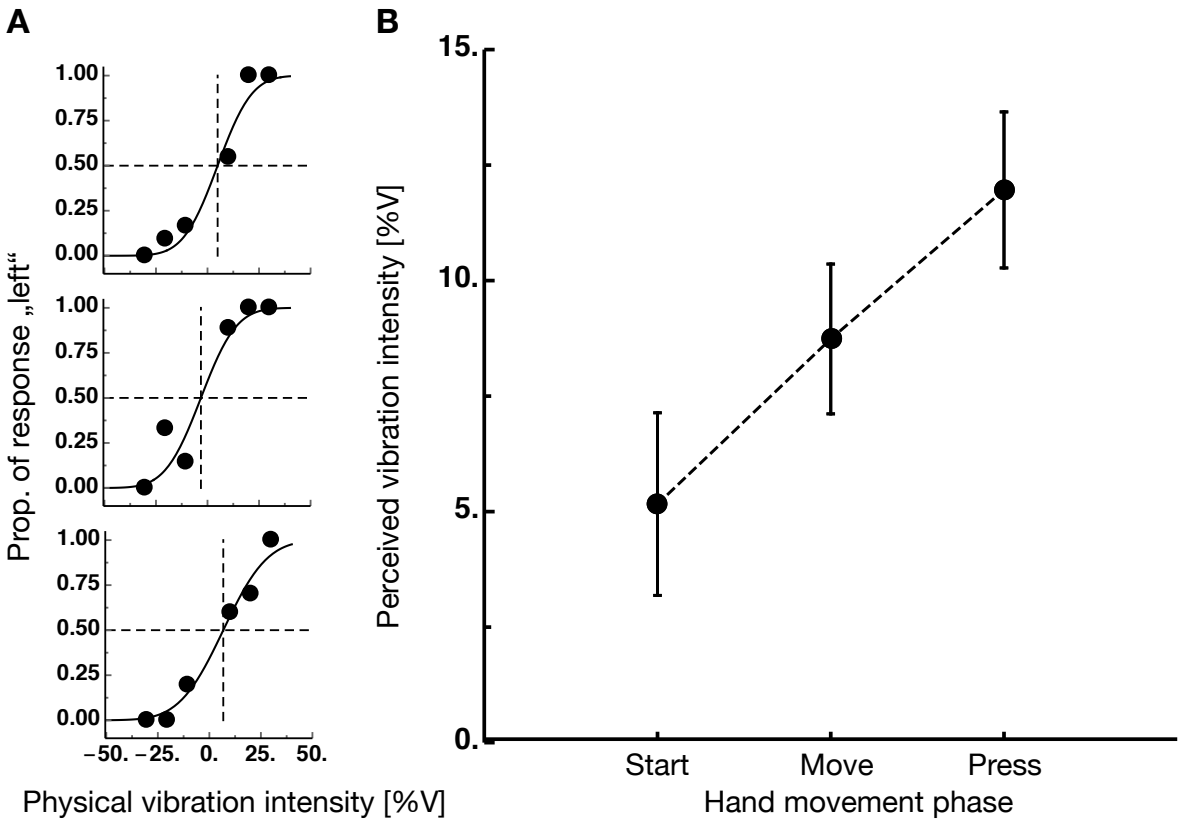

Figure 2. Results of Experiment 1. (A) Psychometric functions of an example participant for the three movement times. Proportions of left responses are shown against physical vibration intensity. (B) Average perceived vibration intensities for the three hand movement times. The abscissa shows the deviation from the standard stimulus (positive numbers represent overestimation of vibration intensity). Error bars represent S.E.M.

Experiment 2

In half of the trials in Experiment 2 a tone was played when subjects pressed the button and in the other half the tone was played when they started the movement. Additionally, in the condition 'tactile', a tactile stimulation was felt on the moving index finger when subjects pressed the button. In the other condition ‘no-tactile’, a tactile stimulation was not felt. A 2 x 2 repeated measures ANOVA with tactile stimulation (‘tactile’ vs. ‘no-tactile’) and hand movement time (start vs. press) as factors and the PSEs of the perceived auditory intensities as the dependent variable was conducted (‘tactile’: M_{start} = -0.81, *SD* = 9.04; M_{press} = -7.58, *SD* = 12.37; ‘no-tactile’: M_{start}= -1.81, *SD* = 12.31; M_{press} = -2.84, *SD* = 10.32). The two main effects for tactile stimulation ($F(1, 24) = 1.302$, $p = .265$, $n_p^2 = .051$) as well as hand movement time ($F(1, 24) = 3.839$, $p = .062$, $n_p^2 = .138$) showed no significance (see Figure

3). The interaction between the hand movement time * stimulation showed a significant difference ($F(1, 24 = 4.71$, $p = .04$, $n_p^2 = .164$). We also analyzed JNDs with a repeated measures 2 x 2 ANOVA with tactile stimulation ('tactile' vs. 'no-tactile') and hand movement time (start vs. press) as factors ('tactile': $M_{start} = 28.02$, $SD = 30.9$; $M_{press} = 22.35$, $SD = 20.18$; 'no-tactile': $M_{start} = 19.08$, $SD = 12.39$; $M_{press} = 15.71$, $SD = 13.51$, $n_p^2 = .227$). No significant interaction was found ($F(1, 24 = 192$, $p = .665$, $n_p^2 = .008$). A post hoc analysis (Bonferroni corrected) revealed that this significance is to be found between the condition of start and press in the tactile condition ($MD = 6.77$, $SEM = 2.39$, 95% CI [0.148, 13.39], $p = .043$). No significance was found between the other conditions ($p > .176$).

The main effect of hand movement time ($F(1, 24) = 1.519$, $p = .230$, $n_p^2 = .060$) was not significant. However, there was a main effect for the tactile stimulation ($F(1, 24) = 6.24$, $p = .020$, $n_p^2 = .206$).

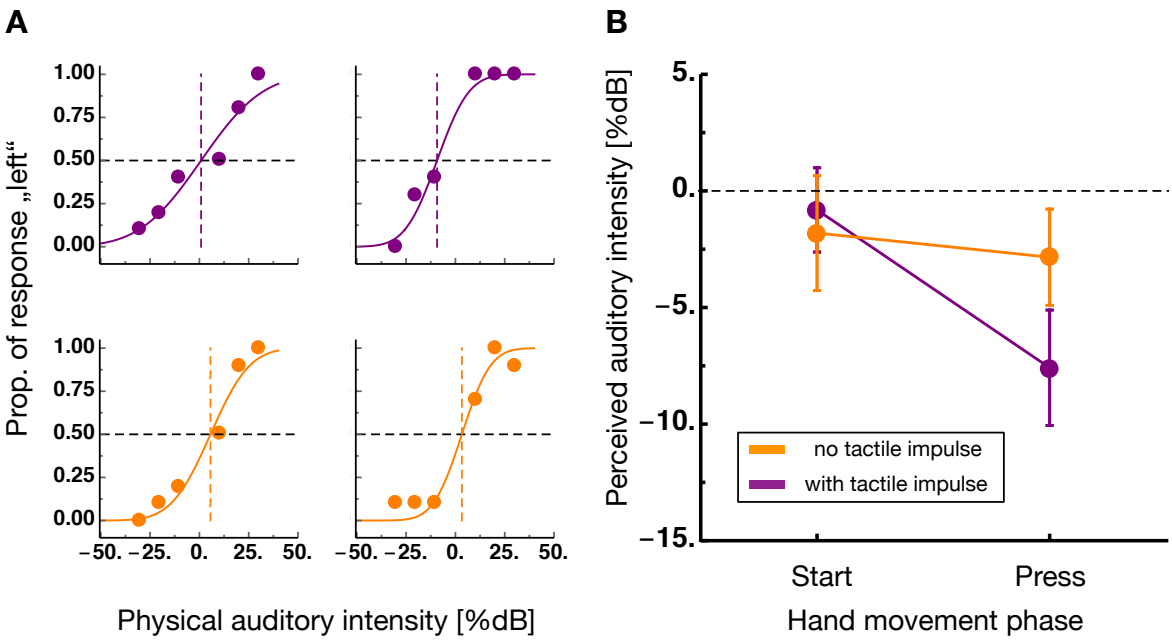

Figure 3. Results of Experiment 2. (A) Psychometric functions of an example participant for the two conditions. Proportions of left responses are shown against physical auditory intensity. (B) Average perceived sound intensities from session with (shown in purple) and without (shown in orange) tactile stimulation for sounds presented at the start and the press time of the movement. The abscissa shows the deviation from the standard stimulus (positive numbers represent overestimation of auditory intensity). Error bars represent S.E.M.

Discussion

In this study we investigated whether a boost of attentional resources at the time of a button pressing movement is responsible for sensory attenuation of self-generated sounds. In Experiment 1 we asked if in a goal-directed button pressing movements, tactile sensitivity is increased at the time the hand makes contact with the button. We found that apparent tactile stimulus intensity was higher at the time when the hand reaches the movement goal than before movement onset or during movement. This finding demonstrates that tactile attention builds up at the time the hand reaches the goal object and transiently increases tactile sensitivity. Previous studies found a reduction of tactile sensitivity during arm movements, a phenomenon known as gating (Chapman et al., 1987). However, in these experiments body parts, for instance the elbow, were probed that did not receive tactile sensations of the goal object. Tactile attention shifts around movements have been tested previously (Juravle et al., 2010). However, here tactile sensitivity was not tested at the time the hand made contact with the object. This time point is special because at that moment the hand receives feedback about the success of its movement. Tactile feedback about movement termination is necessary to stop movement execution.

In Experiment 2 we wondered whether this boost of tactile sensitivity we observed in Experiment 1 would lead to a decrease of auditory sensitivity. To this end, we tested sensory attenuation for sounds with and without a tactile impulse when the virtual button was pressed. Auditory tones were perceived less intensely at button press when tactile feedback was presented. In the condition in which no tactile stimulus was presented and no attentional resources were required for its processing, sensory attenuation was virtually absent.

Attention shifts are known to amplify neural responses and perceived intensity (Desimone & Duncan, 1995; Posner & Dehaene, 1994; Posner & Petersen, 1990), thus explaining the increase in tactile and the decrease in auditory sensitivity. Why would attentional prioritization of the tactile modality create an imbalance between the tactile and the auditory modalities? This linkage might be explained by a close neural connectivity of both modalities. Coactivation of the somatosensory and the auditory cortex have been

reported previously (Butler et al., 2012; Convento et al., 2018; Iguchi et al., 2007; Nordmark et al., 2012; Schürmann et al., 2006) and an influence of attention on these two cortical systems was already described by Gescheider and colleauges (1975).

Most research on sensory attenuation of sounds has focused on the suppression of the N1 amplitude in the EEG. Consistent with our results, three studies found that prediction of sensory consequences is not necessary for sensory attenuation of sounds to occur. When self- and externally generated stimuli were presented within the same experimental block, Baess et al (2011) found that N1 suppression for self-generated stimuli was even stronger. Furthermore, a study also showed that sensory attenuation occurs when stimuli are not predictable but merely coincide with a button press (Horváth et al., 2012; Lange, 2011). In a recent study, in addition to temporal predictability, the influence of temporal control on the N1 amplitude was assessed (Harrison et al., 2021). Sensory attenuation could still be measured when each of these factors was controlled for. Attention is another variable, known to influence the N1 amplitude. Attending away from an auditory stimulus, reduces the amplitude (Mulert et al., 2005). However, studies have shown that sensory attention prevails when attention is controlled for. Timm and colleagues (2014) intermixed self- and externally generated sounds and visual stimuli within one block and asked subjects to attend either to the sounds, the visual stimuli or the button presses. The N1 amplitude was not affected by these attention modulations. With a topographical and tomographical analysis, Saupe et al. (2013) could show that attention and sensory attenuation produce separate neural effects. These studies demonstrate that varying attention demands do not change neural sensory attenuation effects or that the former and the letter can be distinguished in neural activations. However, this does not rule out that tactile attention reduces neural resources for auditory processing. Consistent with our theory stating that tactile processing induces sensory attenuation of sounds, Horváth (2014) found that the N1 and P2 attenuation is stronger in the condition in which there is

sensory contact with the computer keyboard compared to a condition in which such contact does not occur.

A limitation of our study might consist in the combination of the virtual button and the presentation of the tactile impulse, which subjects did not experience before participating in the experiment. However, with this setup we could replicate the sensory attenuation effect. The idea that a sensorimotor contingency between the button press and the ensuing sensory effect must be established before the start of the experiment is based on a theoretical assumption about sensory attenuation that might be incorrect. Three EEG studies found that prediction of sensory consequences is not necessary for sensory attenuation of sounds to occur. When self- and externally generated stimuli were presented within the same experimental block, Baess et al (2011) found that N1 suppression for self-generated stimuli was even stronger. Furthermore, a study also showed that sensory attenuation occurs when stimuli are not predictable but merely coincide with a button press (Horváth et al., 2012; Lange, 2011).

In conclusion, our data suggest that during goal-directed hand movements attention transiently boosts tactile sensitivity at the time the hand reaches the goal object. This increase produces an imbalance between the tactile and the auditory domain, leading to reduced attentional resources in the latter and thereby to sensory attenuation for sounds.

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Open Practices Statement

Neither of the studies reported in this article was formally preregistered. The data of the study are available at https://osf.io/edt74/. Requests for analysis scripts can be sent via email to the lead author.

Competing interests

The authors declare no competing interests.

Author Contributions statement

EZ developed the study concept. All authors contributed to the study design. Testing and data collection were performed by CF and MF. CF performed the data analysis and interpretation under the supervision of EZ. All authors contributed to writing the several drafts of the paper and approved the final version of the manuscript for submission.

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