Motor attention induces sensory attenuation for external events

Clara Fritz[1,*], Mayra Flick[1], Eckart Zimmermann[1]

[1]Institute for Experimental Psychology, Heinrich Heine University Düsseldorf, Germany

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* contact: clara.fritz@uni-duesseldorf.de

Abstract

A doorbell sounds less loud to us if we ring it ourselves than if someone else pushes the button. In general self-produced stimuli appear attenuated to us compared to stimuli generated by others. The effect is known as sensory attenuation. 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. In a second experiment, participants pushed a button and estimated the loudness of sounds. We found sensory attenuation for sounds only when tactile feedback was provided at the time of reaching the movement goal. In a third experiment, we found that this interaction between a tactile and an auditory event did not occur when the hands remained passive without movement. These data indicate that sensory attenuation for sounds occurs because tactile attention is boosted at the time a movement reaches its goal, leaving reduced attentional resources for the auditory modality.

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

Introduction

Self-generated sensory events are perceived as less intense compared to events that are externally produced. This phenomenon has been termed *sensory attenuation* [1]. Research into sensory attenuation contains different strands. Sensory attenuation can occur for body-related touch [2] and for external events, like a sound that is produced by a button press [3]. Furthermore, studies use behavioral methods to investigate the perceived intensity of self-produced and / or psychophysiological sensations to focus on the N1 component of the auditory evoked potential [4]. The amplitude of the N1 component is reduced when sounds are actively produced by the participants compared to passive listening conditions [5]. It is unclear how the several stands relate to each other [6]. It has been argued that, although sensory attenuation for body-related and for external events share common elements, evidence suggests that the two effects rely on separate neural mechanisms [7]. For instance, sensory attenuation of self-touch is spatially selective for the goal location of the touching movement [8–10]. It can be predicted precisely because - unlike in most experiments on attenuation of external events - the position of the tactile sensation matches exactly the position of the touch. Furthermore, arguments have been raised against a direct relationship between the sensitivity reduction observed in behavior and the reduction of the N1 component [11].

In the present study, we aimed to test the hypotheses that in goal-directed hand movements, tactile attention builds up at the predicted time when the hand will make contact with the desired object. Pre-motor induced attention shifts are known to occur for several movements: For eye [12]- and for pointing [13] 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 [14]. A similar predictive attention shift has been found for pointing movements. Deubel and colleagues (1998) [15] 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 [16]. 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 [16]. However, thresholds were not tested in the study at the time when the hand makes contact with the object.

Response amplification is a common feature of selective attention shifts [17–19]. 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 their functional connectivity. The human somatosensory cortex co-activates with auditory cortex during the processing of vibrations and texture [20–23]. Convento and colleagues (2018) [24] 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) [25]. 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 three 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 [16,26]. 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 [16]. We tested tactile thresholds during closed-loop button-press movements that are commonly used to measure sensory attenuation of external events [27].

Second, does attention processing the tactile sensation during a button press determine attenuation for sounds that are contingent on the button press?

Third, is the putative interaction of tactile stimulus presentation and sensory attenuation for sounds dependent on active movements?

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. Therefore, at the exact moment of button press tactile feedback could be provided to the participants moving hand. 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. In Experiment 3, we asked if the putative interaction between tactile and acoustic sensory information occurs only during movements.

Methods

Participants

A total of 30 study participants took part in Experiment 1. 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 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).

Experiment 3 contained 25 right-handed participants with unrestricted vision or vision correction (age: 19 - 64 years [M_{age} = 31.55, *SD* = 14.34], sex: 10 male, 15 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.

General materials

The Experiments 1 and 2 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 movement (see Figure

1). 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 (70% 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 40-60% and 80-100% 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).

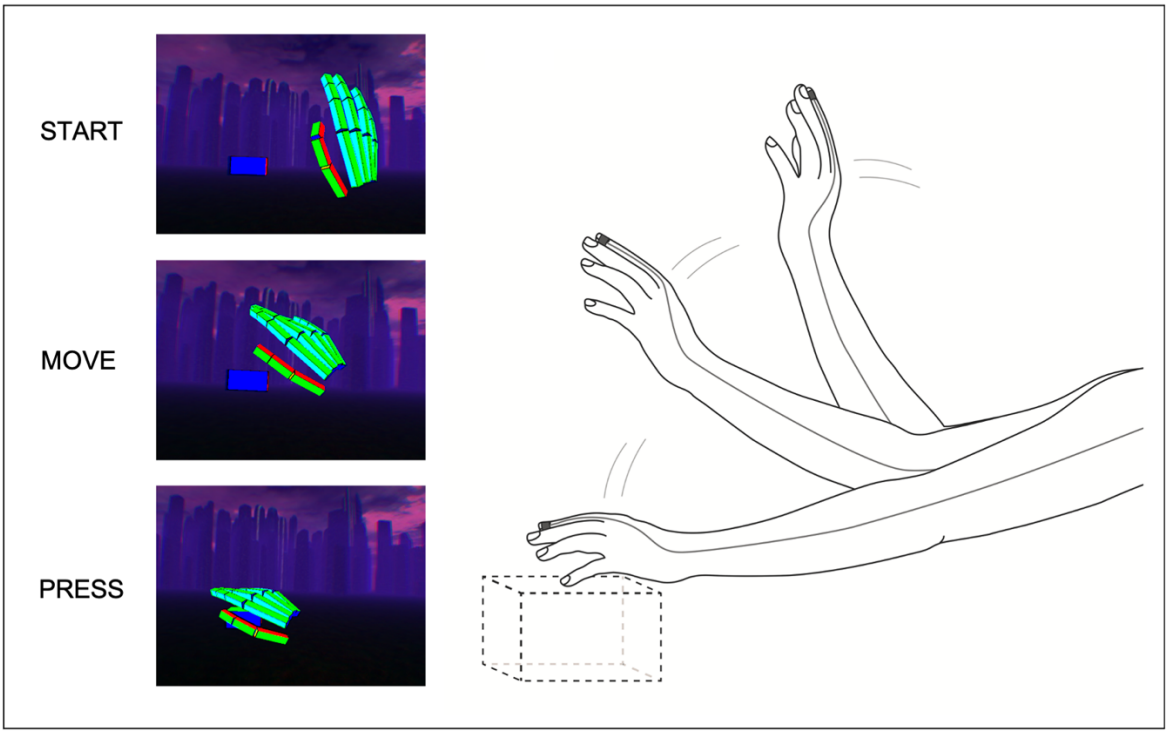

Figure 1. Experimental setup. Participants were asked to perform a goal-directed hand movement to press a virtual button. During the movement the hand starts perpendicular to the button (start), is then moved down towards the button (move) and ends the movement with a button press (press). The mini vibrators 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.

Procedure in Experiment 3

To identify whether the putative interaction of tactile stimulus presentation and sensory attenuation for sounds is dependent on the active movement, participants did not perform the goal-directed hand movement during the third experiment. The participants were placed in front of a table with headphones on and were told to keep their hands rested on the table without any movement. During the test phase they saw a black screen the whole

time and heard two different tones via headphones. The first tone was played with 63.3 dB (50% of maximum intensity of the MacBook). The second tone, as a comparison tone, was presented 700ms later either with 80-60% or 40-20% of the maximum auditive intensity.

After each trial participants had to decide which tone was perceived louder by using a foot pedal placed under the table. Participants had to press either the right button of the foot pedal, when the first tone was perceived as louder or the left button when the second tone was perceived as louder (or vice versa). After entering the answer, the next trial started immediately. In the first condition, no tactile stimulation was presented during the discrimination task ('no-tactile'). In the second condition ('tactile'), a mini-vibrator was attached to the participants right index finger. A vibration with 70% of maximum intensity was felt on the index finger paired with the first tone. Headphones prevented auditory perception of the tactile stimulus. The order of 'tactile' vs. 'no-tactile' was randomized between participants.

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 200 ms before the go-signal, the second all trials in which tactile stimulation occurred equal to or more than 200 ms after the go-signal and the third phase all trials in which tactile stimulation occurred concurrently with the button press. For all three experiments data were averaged for all 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'. To analyze data in Experiment 3 a t-test for repeated measures was used. Data were divided in 'tactile' vs. 'no tactile’ during the discrimination task.

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

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} = 58.73, *SD* = 8.73; M_{move} = 55.16, *SD* = 10.64; M_{press}= 61.96, *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 revealed that there was a significant difference between the start and mid movement time (*MD* = 3.57, *SEM* = 1.56, 95% CI [-0.38, 6.77], $p = .03$), between the start and press movement time (*MD* = 3.27, *SEM* = 1.37, 95% CI [-0.42, 6.03], $p = .026$) as well as the mid and press movement time (*MD* = 6.80, *SEM* = 2.03, 95% CI [2.63, 10.96], $p = .002$). We also analyzed JNDs with a one-way repeated measures ANOVA (M_{start}= 12.89, *SD* = 16.45; M_{move}= 18.27, *SD* = 17.88; M_{press} = 16.23, *SD* = 17.36). No significant main effect was found here ($F(2, 56) = 1.757$, $p = .182$, $n_p^2 = .059$).

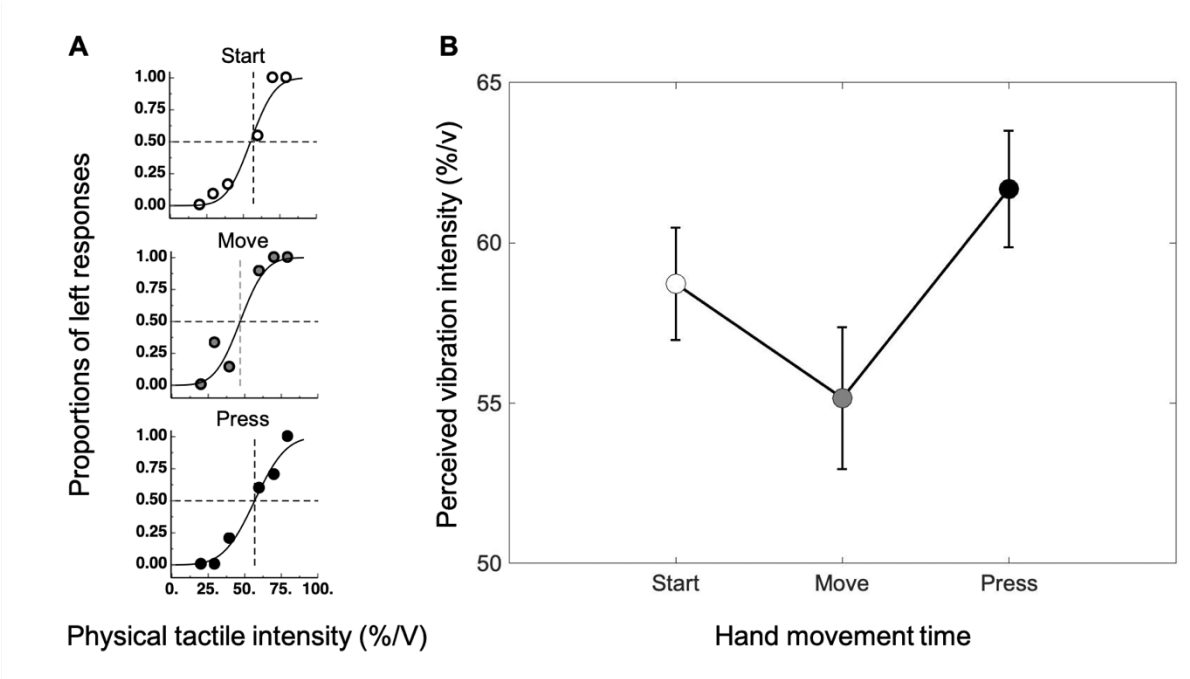

Figure 2. Results of Experiment 1. (A) Psychometric functions of one participant for the three movement times. Proportions of left responses are shown against physical tactile intensity. (B) Average perceived vibration intensities for the three hand movement times. Error bars represent S.E.M.

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} = 49.19, *SD* = 9.04; M_{press} = 42.42, *SD* = 12.37; ‘no-tactile’: M_{start}= 48.19, *SD* = 12.31; M_{press} = 47.16, *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). 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).

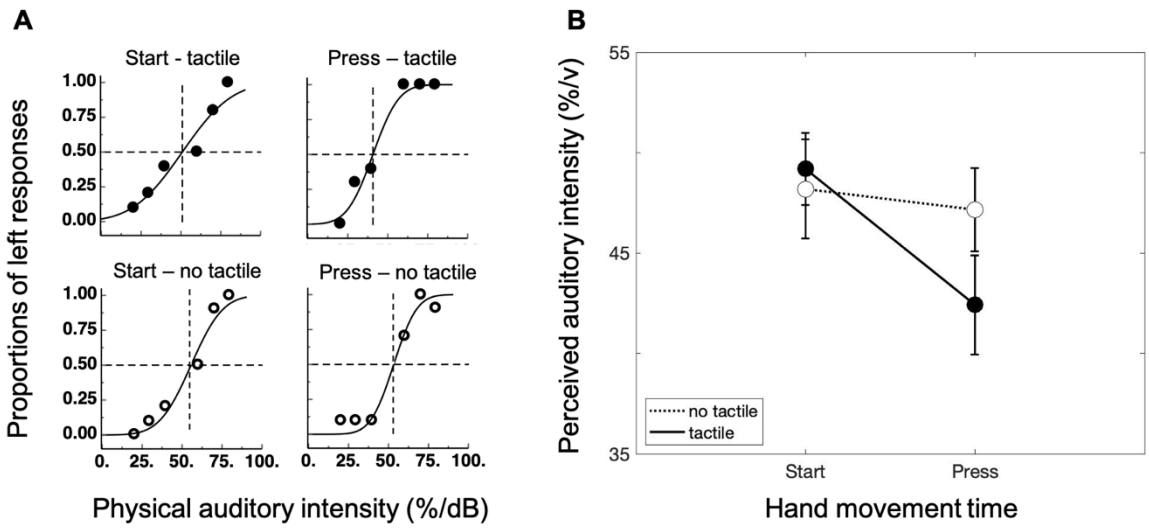

Figure 3. Results of Experiment 2. (A) Psychometric functions of one participant for the three conditions. Proportions of left responses are shown against physical tactile intensity. (B) Average perceived sound intensities from session with (shown in black) and without (shown in white) tactile stimulation for sounds presented at the start and the press time of the movement. Error bars represent S.E.M.

Experiment 3

The aim of Experiment 3 was to answer the question whether the putative interaction of tactile stimulus presentation and sensory attenuation for sounds is dependent on active movements. Experiment 3 was not conducted in VR and did not contain a goal-directed hand movement. Data was divided into 'tactile' (a tactile stimulation was felt during the sound discrimination) and 'no-tactile' (absence of tactile stimulation during sound discrimination). A t-test for repeated measures revealed no significant differences in the PSEs for 'tactile' (*M* = 52.65, *SD* = 8.131) and 'no-tactile' (*M* = 50.069, *SD* = 6.889): (*t*(24) = 1.562, 95% CI [-0.829,

5.99], p = .131, d = .304). Also a repeated measures t-test for JNDs showed no significant effects for the difference between 'tactile' (M = 11.86, SD = 9.335) and 'no-tactile' (M = 12.891, SD = 10.01): $t(24)$ = -0.425, 95% CI [-6.015, 3.961], p = .675, d = .086). The results for Experiment 3 are presented in Fig. 4.

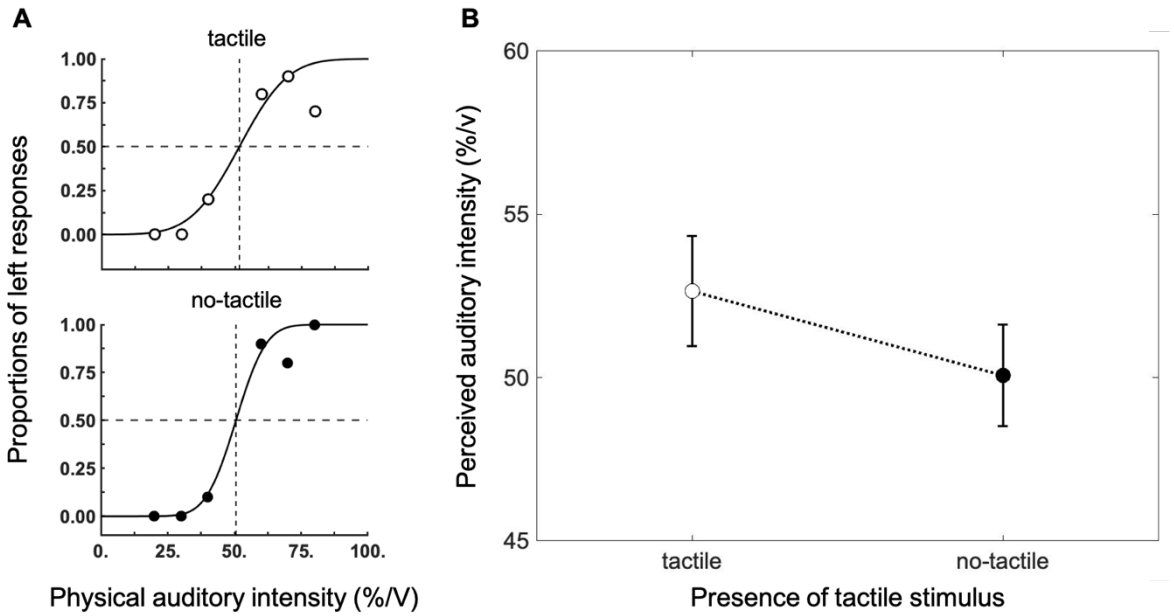

Figure 4. Results of Experiment 3. (A) Psychometric functions of one participant for the two conditions. Proportions of left responses are shown against physical tactile intensity. (B) Average perceived sound intensities from session with and without tactile stimulation. Error bars represent S.E.M.

Discussion

In this study we investigate whether a boost of attentional resources at the time of pressing a button is responsible for sensory attenuation of self-generated sounds. In Experiment 1 we asked if in a goal-directed button pressing movement, tactile sensitivity is increased at the time the hand makes contact with the button. First, we found that apparent tactile stimulus intensity at the time when the hand reaches the movement goal was higher than before movement onset or during movement. This finding supports the hypothesis that tactile attention builds up at the time the hand reaches the goal object and transiently increases tactile sensitivity. Second, we found that during movement execution tactile sensitivity is reduced, a phenomenon known as gating [26,29]. Recently, evidence was provided that gating and sensory attenuation are separate effects [29]. Tactile attention shifts around movements have been tested previously [16]. However, in their study tactile sensitivity was not tested at the time the hand made contact with the object. We assume that this time point is special because at that moment the hand receives feedback about the success of its movement. Tactile feedback about movement termination might be important to stop movement execution, thus justifying a prioritized neural processing of tactile sensations at that time.

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 as less intense when tactile feedback was presented. In the condition in which no tactile stimulus was presented, sensory attenuation was virtually absent. Sensory attenuation for sounds depends on the presence of a tactile impulse at the time of contact with the goal object. With regard to the findings of both, Experiment 1 and 2, we suggest that a boost of attention to the tactile modality decreases resources for the processing of the auditory modality. Attention shifts are known to amplify neural responses and perceived intensity [17–19], 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 [20–24] and an influence of attention on these two cortical systems was already described by Gescheider and colleagues (1975) [25]. One might wonder - if attention shifts to the hand transiently around the time the hand touches the object - why the presence of a tactile stimulus is necessary to produce the sensory attenuation for sounds. If attention shifts predictively, sensory attention for sounds should occur when a tactile stimulus is presented and in its absence. We assumed that only in the presence of tactile stimulation attention would be bound to the tactile modality. Deubel and Schneider (1996) [12] showed that attentional shifts preceding the execution of a saccade to a stationary target led to an increase in visual discrimination performance at the saccade goal, but not at other locations. In other words, at the time of saccade onset, attention is bound to the target position. However, a recent study showed that attentional shifts preceding saccades which are executed to an extinguished target allow attention to spread [30]. Thus, in the absence of the visual target, attention is no longer bound to the goal location of the saccade.

The results from Experiment 2 do not demonstrate that a movement is necessary to produce sensory attenuation of sounds by tactile stimulation. Sensory attenuation occurred when the tone was played at the time when the hand pressed the virtual button. Only in this condition the tactile and the auditory stimuli were presented simultaneously. Sensory attenuation in this experiment could result from temporal coincidence of both stimuli. Therefore, in Experiment 3 we tested auditory perception in the presence and absence of tactile stimuli without movements. No effect of the tactile impulse on auditory sensitivity was found. Although this result rules out that the mere simultaneous presentation of a tactile and an auditory stimulus is not sufficient to evoke sensory attenuation, it is still an open question whether an attention shift in a passive condition like in Experiment 3 would produce sensory attenuation. In Experiment 2 subjects could predict the time they would reach the virtual

button and thus anticipate the time of the tactile stimulus. No such cue was available in Experiment 3 that would have allowed attention to build up at the right moment in time.

In the last decade, the influence of several factors has been determined which might have confounding influence on the N1 amplitude. When actively producing a stimulus, subjects can predict the temporal occurrence of the stimulus. When self- and externally generated stimuli were presented within the same experimental block, Baess et al (2011)[31] 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 [32]. In a recent study, in addition to temporal predictability, the influence of temporal control on the N1 amplitude was assessed [33]. 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 [34]. However, studies have shown that sensory attention prevails when attention is controlled for. Timm et al. (2014) [3] 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)[35] 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. To the best of our knowledge, only one study modified the tactile stimulus in the button pressing task and did find an effect on the N1 attenuation [35].

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.

References

1. Blakemore, S.-J., Frith, C. D. & Wolpert, D. M. Spatio-Temporal Prediction Modulates the Perception of Self-Produced Stimuli. *J. Cogn. Neurosci.* **11**, 551–559 (1999).
2. Bays, P. M., Flanagan, J. R. & Wolpert, D. M. Attenuation of Self-Generated Tactile Sensations Is Predictive, not Postdictive. *PLoS Biol.* **4**, e28 (2006).
3. Timm, J., SanMiguel, I., Keil, J., Schröger, E. & Schönwiesner, M. Motor Intention Determines Sensory Attenuation of Brain Responses to Self-initiated Sounds. *J. Cogn. Neurosci.* **26**, 1481–1489 (2014).
4. Bäß, P., Jacobsen, T. & Schröger, E. Suppression of the auditory N1 event-related potential component with unpredictable self-initiated tones: Evidence for internal forward models with dynamic stimulation. *Int. J. Psychophysiol.* **70**, 137–143 (2008).
5. Lange, K. The reduced N1 to self-generated tones: An effect of temporal predictability?: N1 reduction and temporal predictability. *Psychophysiology* **48**, 1088–1095 (2011).
6. Horváth, J. The role of mechanical impact in action-related auditory attenuation. *Cogn. Affect. Behav. Neurosci.* **14**, 1392–1406 (2014).
7. Dogge, M., Custers, R. & Aarts, H. Moving Forward: On the Limits of Motor-Based Forward Models. *Trends Cogn. Sci.* **23**, 743–753 (2019).
8. Bays, P. M., Wolpert, D. M., Haggard, E. P., Rosetti, Y. & Kawato, M. Predictive attenuation in the perception of touch. *Sensorimotor Found. High. Cogn.* 339–358 (2008).
9. Knoetsch, F. & Zimmermann, E. The spatial specificity of sensory attenuation for self-touch. *Conscious. Cogn.* **92**, 103135 (2021).
10. Kilteni, K., Houborg, C. & Ehrsson, H. H. Rapid learning and unlearning of predicted sensory delays in self-generated touch. *eLife* **8**, e42888 (2019).
11. Palmer, C. E., Davare, M. & Kilner, J. M. Physiological and Perceptual Sensory Attenuation Have Different Underlying Neurophysiological Correlates. *J. Neurosci.* **36**, 10803–10812 (2016).
12. Deubel, H. & Schneider, W. X. Saccade target selection and object recognition:

Evidence for a common attentional mechanism. *Vision Res.* **36**, 1827–1837 (1996).

13. Baldauf, D., Wolf, M. & Deubel, H. Deployment of visual attention before sequences of goal-directed hand movements. *Vision Res.* **46**, 4355–4374 (2006).
14. Baldauf, D. & Deubel, H. Properties of attentional selection during the preparation of sequential saccades. *Exp. Brain Res.* **184**, 411–425 (2008).
15. Deubel, H., Schneider, W. X. & Paprotta, I. Selective Dorsal and Ventral Processing: Evidence for a Common Attentional Mechanism in Reaching and Perception. *Vis. Cogn.* **5**, 81–107 (1998).
16. Juravle, G., Deubel, H., Tan, H. Z. & Spence, C. Changes in tactile sensitivity over the time-course of a goal-directed movement. *Behav. Brain Res.* **208**, 391–401 (2010).
17. Desimone, R. & Duncan, J. Neural Mechanisms of Selective Visual Attention. *Annu. Rev. Neurosci.* **18**, 193–222 (1995).
18. Posner, M. I. & Dehaene, S. Attentional networks. *Trends Neurosci.* **17**, 75–79 (1994).
19. Posner, M. I. & Petersen, S. E. The Attention System of the Human Brain. *Annu. Rev. Neurosci.* **13**, 25–42 (1990).
20. Butler, J. S., Foxe, J. J., Fiebelkorn, I. C., Mercier, M. R. & Molholm, S. Multisensory Representation of Frequency across Audition and Touch: High Density Electrical Mapping Reveals Early Sensory-Perceptual Coupling. *J. Neurosci.* **32**, 15338–15344 (2012).
21. Iguchi, Y., Hoshi, Y., Nemoto, M., Taira, M. & Hashimoto, I. Co-activation of the secondary somatosensory and auditory cortices facilitates frequency discrimination of vibrotactile stimuli. *Neuroscience* **148**, 461–472 (2007).
22. Nordmark, P. F., Pruszynski, J. A. & Johansson, R. S. BOLD Responses to Tactile Stimuli in Visual and Auditory Cortex Depend on the Frequency Content of Stimulation. *J. Cogn. Neurosci.* **24**, 2120–2134 (2012).
23. Schürmann, M., Caetano, G., Hlushchuk, Y., Jousmäki, V. & Hari, R. Touch activates human auditory cortex. *NeuroImage* **30**, 1325–1331 (2006).
24. Convento, S., Rahman, Md. S. & Yau, J. M. Selective Attention Gates the Interactive

Crossmodal Coupling between Perceptual Systems. *Curr. Biol.* **28**, 746-752.e5 (2018).

25. Gescheider, G. A., Sager, L. C. & Ruffolo, L. J. Simultaneous auditory and tactile information processing. *Percept. Psychophys.* **18**, 209–216 (1975).
26. Chapman, C. E., Bushnell, M. C., Miron, D., Duncan, G. H. & Lund, J. P. Sensory perception during movement in man. *Exp. Brain Res.* **68**, (1987).
27. Weiss, C., Herwig, A. & Schütz-Bosbach, S. The Self in Social Interactions: Sensory Attenuation of Auditory Action Effects Is Stronger in Interactions with Others. *PLoS ONE* **6**, e22723 (2011).
28. Rushton, D. N., Roghwell, J. C. & Craggs, M. D. Gating of somatosensory evoked potentials during different kinds of movement in man. *Brain* **104**, 465–491 (1981).
29. Kilteni, K. & Ehrsson, H. H. *Predictive attenuation of touch and tactile gating are distinct perceptual phenomena*. http://biorxiv.org/lookup/doi/10.1101/2020.11.13.381202 (2020) doi:10.1101/2020.11.13.381202.
30. Szinte, M., Puntiroli, M. & Deubel, H. The spread of presaccadic attention depends on the spatial configuration of the visual scene. *Sci. Rep.* **9**, 14034 (2019).
31. Baess, P., Horváth, J., Jacobsen, T. & Schröger, E. Selective suppression of self-initiated sounds in an auditory stream: An ERP study: Selective suppression of self-initiated sounds. *Psychophysiology* **48**, 1276–1283 (2011).
32. Horváth, J., Maess, B., Baess, P. & Tóth, A. Action–Sound Coincidences Suppress Evoked Responses of the Human Auditory Cortex in EEG and MEG. *J. Cogn. Neurosci.* **24**, 1919–1931 (2012).
33. Harrison, A. W. *et al.* Sensory attenuation is modulated by the contrasting effects of predictability and control. *NeuroImage* **237**, 118103 (2021).
34. Mulert, C. *et al.* Sound level dependence of the primary auditory cortex: Simultaneous measurement with 61-channel EEG and fMRI. *NeuroImage* **28**, 49–58 (2005).
35. Saupe, K., Widmann, A., Trujillo-Barreto, N. J. & Schröger, E. Sensorial suppression of self-generated sounds and its dependence on attention. *Int. J. Psychophysiol.* **90**, 300–310 (2013).

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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.

Additional information

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Correspondence: Further information and requests should be directed to Clara Fritz, Institute for Experimental Psychology, Universitätsstraße 1, 40225 Düsseldorf, Germany (clara.fritz@uni-duesseldorf.de).