Sensory Attenuation for external events is produced by a competition for attentional resources

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Author Note

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Abstract

A doorbell sounds less loud to us if we ring it ourselves than if someone else pushes the button. Self-produced stimuli appear attenuated to us compared to stimuli generated by others (Weiss et al., 2011). The effect is known as sensory attenuation for external events. Here, we asked whether this effect results from a competition for attentional resources of sensory events. We first tested whether tactile attention is boosted at the time of pushing a button. We presented a button in a virtual reality setup that allowed to manipulate the time of tactile feedback. 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 the loudness of the sound 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 reveal that sensory attenuation for external events occurs because tactile attention is boosted at the time of a button pressing movement, thereby dragging attention from the auditory modality.

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

Introduction

Sensations of self-produced events appear attenuated. This phenomenon has been observed for auditory (Weiss & Schütz-Bosbach, 2012), visual (Cardoso-Leite et al., 2010) as well as tactile stimuli (Bays et al., 2006). Sensory attenuation for external events, like sounds generated by a button-press, must be distinguished from sensory attenuation for self-touch (Bays et al., 2006). Although both phenomena share common elements, evidence suggests that the two effects rely on separate neural mechanisms (Dogge, 2019). For instance, sensory attenuation of self-touch is spatially selective for the goal location of the touching movement (Bays et al., 2008, Kilteni et al., 2019, Knoetsch & Zimmermann, 2021). 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, the connection between touch and tactile sensation is over-learned across the lifetime whereas the contingency between a movement (e.g. a button press) and an arbitrary external event must be trained to be predictable. However, for external events studies have shown that sensory attenuation occurs even if sounds merely coincide unpredictably with a button press (Horváth et al., 2012, Bäß et al., 2008).

In goal-directed, closed loop, ballistic actions, like button pressing, the event most important to guide internal movement control is the tactile sensation that ensues when the hand makes contact with the goal object. In order to stop the movement when necessary, the sensorimotor system should register this tactile sensation with highest priority. We wondered whether attenuation for external events might be the consequence of attention shifting to the tactile modality at the time of button-press movements, leading to limited attentional resources in the auditory modality. Functional connectivity between the tactile and auditory modality that might provide the basis for a competition of attentional resources has been reported in previous research. The human somatosensory cortex co-activates with auditory cortex during the processing of vibrations and textures (Schürmann et al., 2006; Butler et al., 2012; Nordmark et al., 2012; Iguchi et al., 2007). 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.

A competition for attentional resources is particularly likely in self-produced actions since movements generate an inescapable shift of attention to the goal location of the movement. For instance, 50 ms before execution of a saccade, visual attention is bound to the target location of the eye movement (Deubel & Schneider, 1996). Similar effects have also been shown for goal-directed hand movements such as pointing, grasping, and visual attention. 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. Similar to the attention effects observed at the time of saccades, a target that was close to the goal object of pointing movements had a better discrimination performance than when presented at other locations. We assumed that if tactile attention shifts to the hand that presses a button, less resources might be available in the auditory domain. To create a realistic impression, button pressing was accompanied by a vibrotactile feedback towards the end of movement. Consequently, sound intensity would appear reduced.

We aimed to test 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 (Juravle et al., 2017). 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 ballistic button-press movements that are commonly used to measure sensory attenuation of external events (e.g. 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?

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. 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 23 study participants took part in Experiment 1. For two participants psychometric functions could not be estimated, indicating that the task was not performed correctly. Therefore, the final sample in Experiment 1 consisted of 21 right-handed participants with unrestricted vision or vision correction (age: 18 - 56 years [M_{age} = 27.81, *SD* = 10.97], sex: 10 male, 10 female, 1 diverse).

In Experiment 2 20 participants took part of whom three participants were excluded since psychometric functions could not be estimated. Therefore, the data of 17 right-handed participants with unrestricted vision or vision correction were included in the data analysis (age: 20 - 36 years [M_{age} = 24.33, *SD* = 4.28], sex: 5 male, 13 female).

Experiment 3 contained 20 right-handed participants with unrestricted vision or vision correction (age: 19 - 64 years [M_{age} = 32.55, *SD* = 14.34], sex: 9 male, 11 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 is 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.

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 programmed in Xcode 12 with C++ and 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°), attached to the VR goggles and transferred to a virtual hand in the VR environment. 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

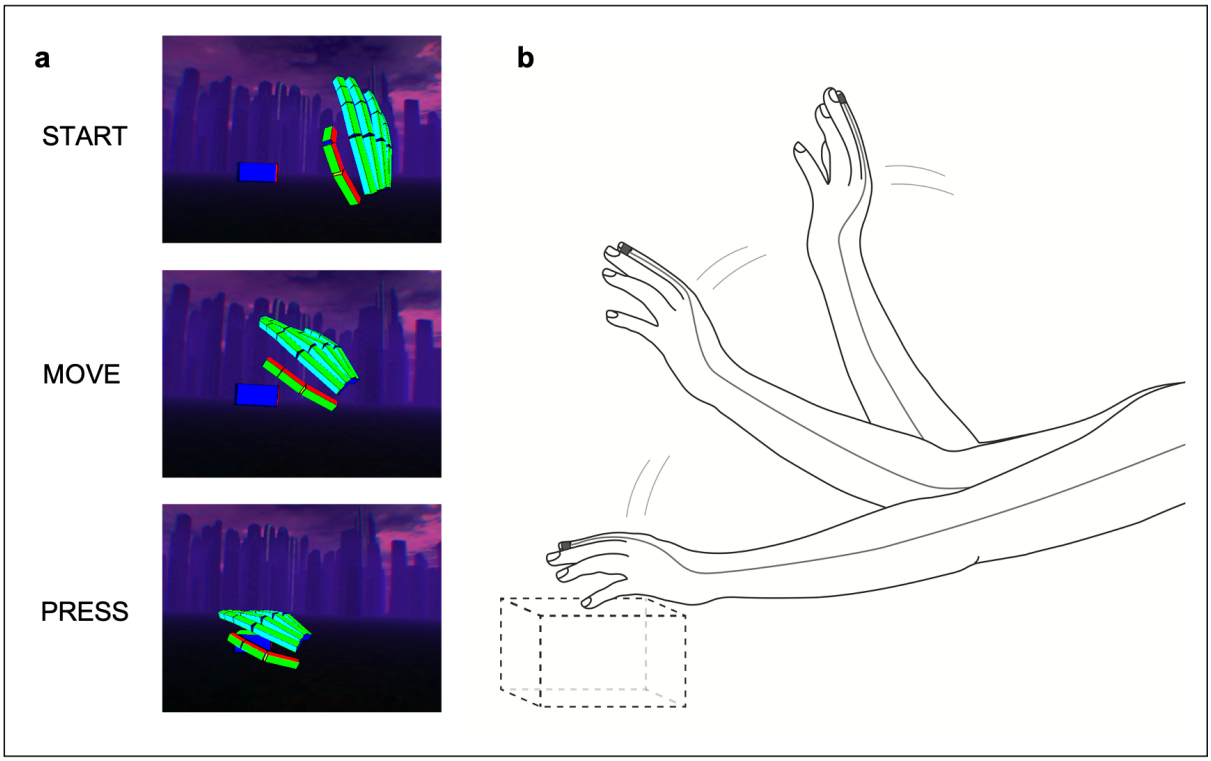
In Experiment 1, participants had to perform a ballistic hand movement to press the virtual button with their right hand. In each trial they made an arm movement starting with the right hand and forearm held up and moved downwards to press the button (see Figure 1). The virtual button went down 5° when 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). 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 (in 6 equidistant steps). After each trial, participants had to decide which vibration was perceived stronger by using a foot pedal, pressing the right button when the first vibration felt stronger and the left button when the second vibration felt stronger. Then, 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



Note. Participants were asked to perform a ballistic 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’. Both experimental conditions were conducted in the same virtual reality setup as Experiment 1. Again, participants were asked to perform a ballistic movement to press the virtual button with the right hand within VR. Here, a tone was presented either during the movement time of starting the movement or when pressing the button. The tone was presented with 50% of

maximum intensity of the MacBook through headphones. The maximum tone level of the MacBook Pro used for the experiments was 63,3 dB. 700 ms after finishing the ballistic movement a comparison tone was played, either with 80%, 70%, 60% or 40%, 30%, 20% of the maximum auditive intensity. Participants were asked to rate which tone was louder by pressing either the right (first tone was louder) or left button (second tone was louder) of the foot pedal placed on the floor. The timing of the first tone (start vs. press movement time) as well as the volume of the comparison tone (20-40% and 60-80%) 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 ballistic 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.

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 ballistic 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 heard two different tones via headphones. The first tone was played with 50% of the maximum auditive intensity of the

MacBook Pro. The second tone, as a comparison tone, was presented 700ms later with either 80%, 70%, 60% or 40%, 30%, 20% of the maximum auditive intensity was presented 700ms later. 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 the right button of the foot paddle, when the first tone was perceived as louder or the left button when the second tone was perceived as louder. 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. 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. 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 a non-parametrical 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/8s9te/.

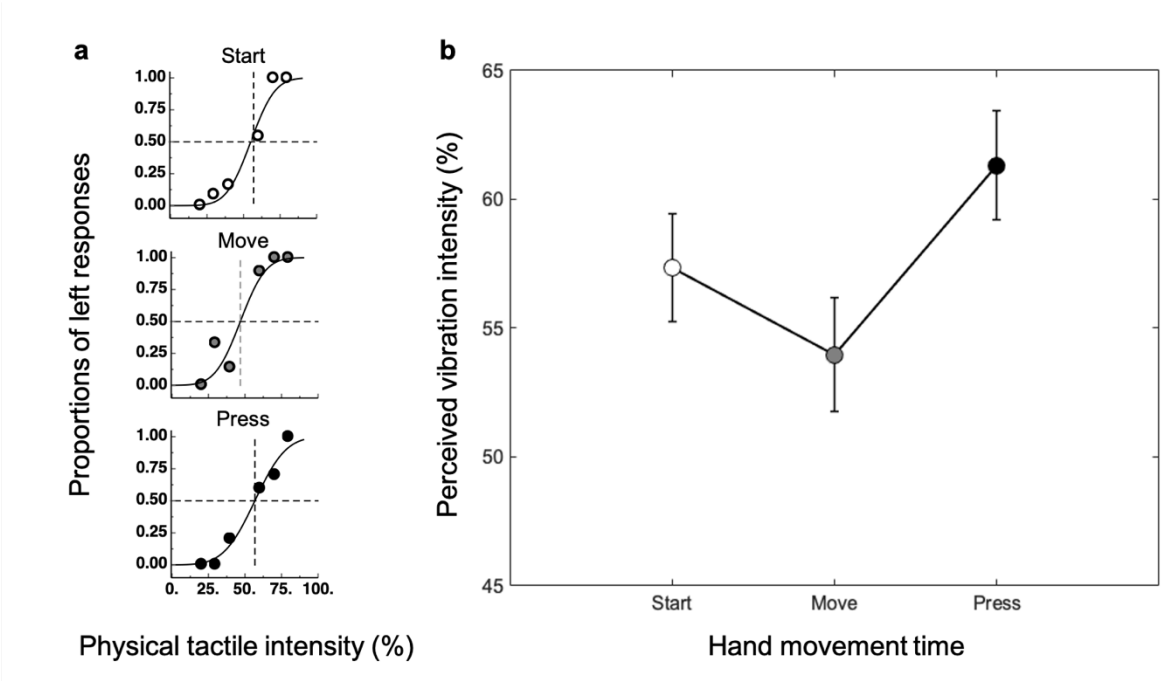
Results

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. Example psychometric functions for two participants are shown in Figure 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} = 57.35, *SD* = 9.52; M_{move} = 53.96, *SD* = 10.15; M_{press}= 61.32, *SD* = 9.72). There was a statistically significant difference between the movement times ($F(2, 40) = 6.33$, $p = .004$, $n_p^2 = .240$). A post hoc analysis revealed that there was no significant difference between the start and mid movement time (*MD* = 3.38, *SEM* = 1.83, 95% CI [-0.44, 7.21], $p = .08$). However, there was a statistically significant difference between the start and press movement time (*MD* = 3.98, *SEM* = 1.79, 95% CI [-0.25, 7.70], $p = .038$) as well as the mid and press movement time (*MD* = 7.26, *SEM* = 2.51, 95% CI [2.12, 12.60], $p = .008$). We also analyzed JNDs with a one-way repeated measures ANOVA (M_{start}= 14.22, *SD* = 17.62; M_{move}= 17.65, *SD* = 14.34; M_{press} = 14.8, *SD* = 17.58). No significant main effect was found ($F(2, 40) = 0.55$, $p = .584$).

Figure 2

Results of Experiment 1



Note. (a) Example psychometric functions 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.

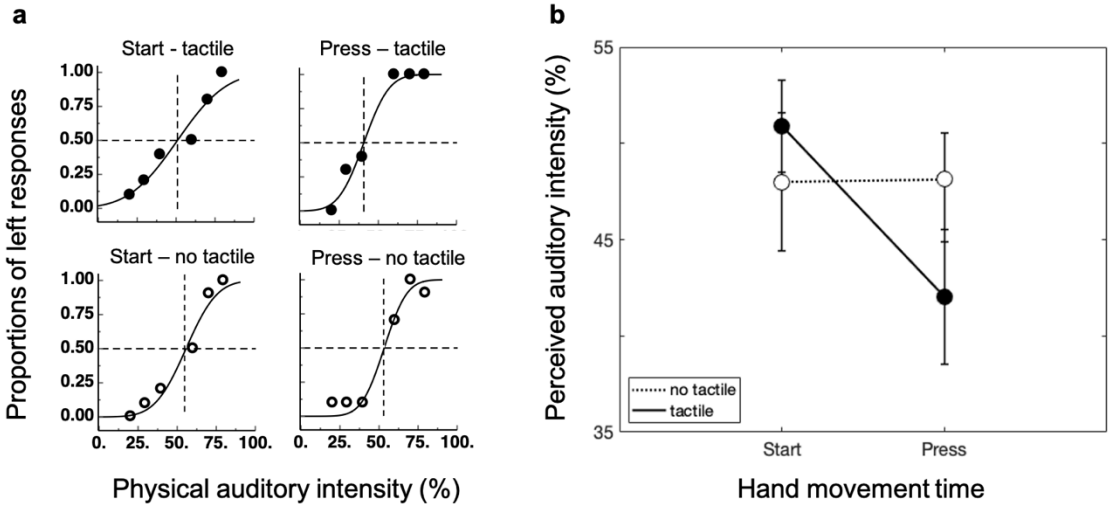
Experiment 2

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 'tactile', a tactile stimulation was felt on the moving index finger when subjects pressed the button. A 2 x 2 repeated measures ANOVA with tactile stimulation (‘tactile’ vs. ‘no-tactile’) and hand movement time (start vs. press) as factors was conducted (‘tactile’: M_{start} = 50.90, *SD* = 9.86; M_{press} = 42.03, *SD* = 14.35; ‘no-tactile’: M_{start} = 47.99, *SD* = 14.83; M_{press} = 48.12, *SD* = 11.68). The two main effects for tactile stimulation ($F(1, 16) = 0.44$, $p = .516$) as well as hand movement time ($F(1, 16) = 2.55$, $p = .130$) showed no significance (see Figure 3). The interaction between the hand movement time * stimulation showed a significant difference ($F(1, 16 = 6.15$, $p = .025$, $n_p^2 = .278$). 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} = 35.12, *SD* = 35.31; M_{press} = 28.55, *SD* = 21.65; ‘no-tactile’: M_{start} = 23.42, *SD* = 12.93; M_{press} = 20.4, *SD* = 13.99). No significant interaction was found ($F(1, 16 = 0.22$, $p = .647$). The main effect of tactile stimulation ($F(1, 16) = 0.80$, $p = .386$) was not significant. However, there was a main effect for the hand movement time ($F(1, 16) = 4.99$, $p = .040$, $n_p^2 = .238$).

Figure 3

Results of Experiment 2



Note. (a) Example psychometric functions 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.

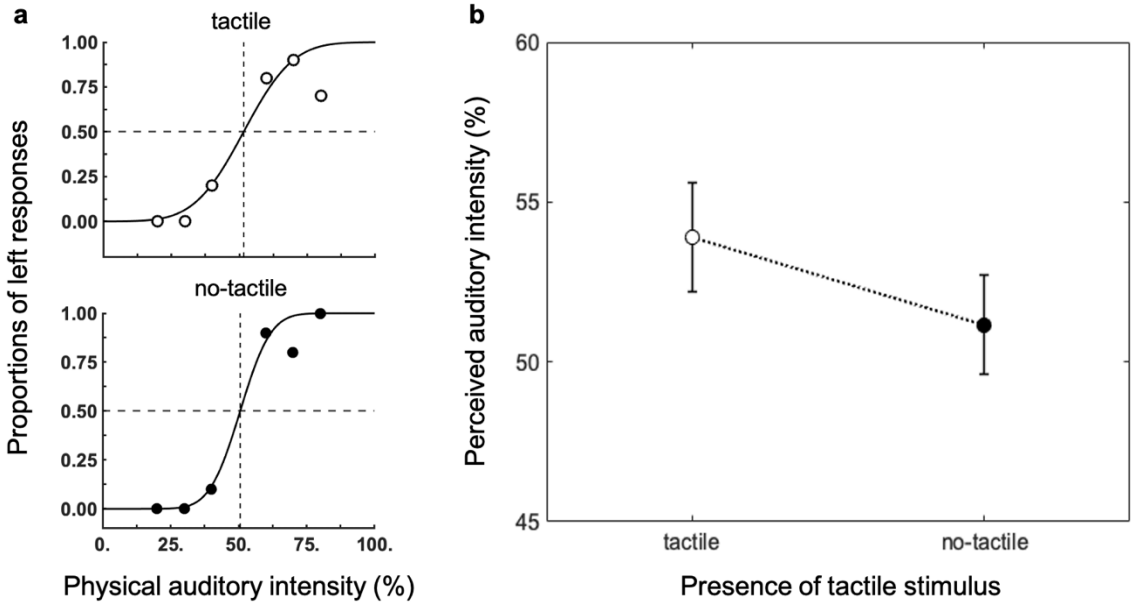
Experiment 3

Experiment 3 was not conducted in VR and without the ballistic hand movement. Therefore, the aim was to answer the question whether the putative interaction of tactile stimulus presentation and sensory attenuation for sounds is dependent on active movements. 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* = 53.895, *SD* = 7.555) and 'no-tactile' (*M* = 51.15, *SD* = 6.93): (*t*(19) = 1.3, 95% CI [-1.67, 7.16], *p* = .208). Also a repeated measures t-test for JNDs showed no significant effects for the difference between 'tactile' (*M* = 14.03, *SD* = 8.84) and 'no-tactile' (*M* = 14.55, *SD* = 9.38): *t*(19) = -0.188, 95% CI [-6.31, 5.27], *p* = .853). The results for Experiment 3 are presented in Figure 4.

Figure 4

Results of Experiment 3



Note. (a) Example psychometric functions 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 investigated whether a competition for 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 ballistic button pressing movement, tactile sensitivity is increased at the time the hand makes contact with the button. 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 indicates that attention in the moving hand is increased at the time of the button press.

For models of selective attention shifts, response amplification is a common feature (Desimone & Duncan, 1995; Posner & Dehaene, 1994; Posner & Petersen, 1990). Earlier brain imaging studies localized neural signatures of tactile attention in primary (Burton et al., 1999; Meyer et al., 1991; Pardo et al., 1991) and secondary (Sinclair & Burton, 1993) somatosensory cortex. Therefore, we reasoned that a movement-induced attentional shift to the tactile modality at the end of the movement would lead to a reduction in attentional resources processing the sensation of the simultaneously appearing sound. Coactivation of the somatosensory and the auditory cortex have been reported previously (Convento et al., 2018; Schürmann et al., 2006; Butler et al., 2012; Nordmark et al., 2012; Iguchi et al., 2007) and an influence of attention on these two cortical systems was already described by Gescheider and colleagues (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 whether auditory sensations were perceived as less intense, because attention was dragged to the tactile modality through the movement-induced attention shift in Experiment 2. Participants judged the intensity of the sounds in two conditions: Virtual button presses were either accompanied by a tactile stimulation or not. For saccades, Deubel and Schneider showed (1996) 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 (Szinte et al., 2019). Thus, in the absence of the visual target, attention is no longer bound to the goal location of the saccade. Following this analogy, we assumed that only in the presence of tactile stimulation attention would be bound to the tactile modality. Indeed, we found attenuation for sounds only when virtual button presses produced a tactile stimulation. In principle, this interaction could also occur without the movement. However, since sensory attenuation of sounds has been shown to occur only for active movements (Timm et al., 2014), in Experiment 3 we tested auditory perception in the presence and absence of tactile stimuli without movements. Here we found no significant differences, supporting the effects of Timm and colleagues (2014) that the ballistic movement was a prerequisite for the given effects of attentional shift.

Our results are consistent with evidence from an EEG study. It is assumed that suppression of the N1 component represents a neural marker of sensory attenuation. 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. This shows the connection between the auditory and tactile systems. Our theory can also explain why sensory attention has been found even when an action-effect contingency has not been learned. Previous research (Lange, 2011; Horváth et al., 2012) found that the mere coincidence between a button press and the visual stimulus is sufficient to measure sensory attenuation. As our current data demonstrate, a shift of attention towards the tactile sensation at the time of button press can explain the effect of sensory attenuation. This means a specific suppression of an action effect is not inevitable necessary to find sensory attenuation.

Sensory attenuation of sounds is often linked to attenuation of self-touch. However, recently it has been argued that separate mechanisms are responsible for both phenomena (Dogge et al., 2019). Attenuation of self-touch is spatially specific such that it only occurs if the touching and touched region match spatially (Bays et al., 2008; Kilteni et al., 2019). This

spatial selectivity requires a mechanism that operates in a body-centered reference frame. Such a mechanism is hardly suited to generate the attenuation of sounds. Therefore, our theory aims at an independent phenomenon of sensory attenuation for sounds.

We conclude that sensory attenuation of external events is produced by a competition of attentional resources. Attention shifting to the tactile modality at the time of reaching the movement goal leads to a lack of attentional resources in the auditory domain, resulting in sensory attenuation of sounds.

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