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Was it me? – Filling the interval between action and effects increases agency but not sensory attenuation

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ABSTRACT

Sensory stimuli resulting from one's own actions are perceptually attenuated compared to identical but externally produced stimuli. This may enable the organism to discriminate between self-produced events and externally produced events, suggesting a strong link between sensory attenuation and a subjective sense of agency. To investigate this supposed link, we compared the influence of filled and unfilled action-effect delays on both, judgements of agency for self-produced sounds and attenuation of the event-related potential (ERP). In line with previous findings, judgments of agency differed between both delay conditions with higher ratings for filled than for unfilled delays. Sensory attenuation, however, was not influenced by filling the delay. These findings indicate a partial dissociation of the two phenomena.

1. Introduction

Our environment comes with many sensory stimuli of different origin. Some of these stimuli are produced by us – like the sound of our own footsteps – whereas other stimuli are produced by external events – like the sound of another agent's footsteps. This distinction of self-produced versus externally produced events has direct consequences for how sensory stimuli with identical physical characteristics are processed: Self-produced sensory events are perceived as less intense than externally produced events, a phenomenon that is typically termed *sensory attenuation* (e.g., Hughes, Desantis, & Waszak, 2013).

Sensory attenuation is often explained in the context of internal forward models (Blakemore, Wolpert, & Frith, 2000; Hughes et al., 2013). According to these models, movement execution entails a copy of the motor command to simulate the movement in advance and predict its consequences (Wolpert & Flanagan, 2001; Wolpert, Ghahramani, & Jordan, 1995). The predicted sensory consequences of the movement – like the sound of our footsteps – are compared to the actually perceived feedback and attenuated if they match (Blakemore, Frith, & Wolpert, 1999).

It is assumed that one function of sensory attenuation is to identify self-produced effects and distinguish them from externally produced ones (Blakemore, Wolpert et al., 2000; Lange, 2011; Wolpert, 1997). This notion suggests a strong link between sensory attenuation and a general sense of agency – i.e., the experience of being the cause of one's own actions and the corresponding effects (e.g., Blakemore, Wolpert, & Frith, 2002; Desantis, Weiss, Schütz-Bosbach, & Waszak, 2012; Shergill, Samson, Bays, Frith, & Wolpert, 2005). A link between sensory attenuation and agency is used to explain, for example, delusions of control or passivity experiences in schizophrenic patients, as schizophrenic patients do not show the typical attenuation of self-produced effects (Blakemore, Smith, Steel, Johnstone, & Frith, 2000; Oestreich et al., 2015; Shergill et al., 2005). This is thought to be due to a malfunction of the forward model and the reason why patients often misattribute self-produced events to external agents (Blakemore et al., 2002). On the other hand, if feelings of agency are manipulated and healthy participants are led to believe that self-produced effects were produced by another person, sensory attenuation can be abolished (Desantis et al., 2012). These findings clearly suggest a mutual relationship of sensory attenuation and agency.

If sensory attenuation and agency are indeed strongly intertwined, they should be influenced similarly when manipulating the relationship between self-produced actions and the corresponding effects. We tested this assumption in the present study. In particular, we drew on previous findings that low temporal contiguity between action and effect diminishes agency. That is: If a delay was inserted between action and effect, participants showed reduced judgements of agency and causality for the effects compared to when effects followed actions immediately (Shanks, 1989; van Elk, Salomon, Kannape, & Blanke, 2014). Importantly for our purposes, the influence of a delay can be reduced by introducing a filler stim-

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ulus during the delay: If participants had to judge whether their button press caused a triangle to light up, participants showed higher judgements if a tone was presented in the delay between action (button press) and effect (triangle lighting up) as compared to a condition without filler tone (Shanks, 1989). The filler effect was shown for delays up to several seconds (Reed, 1999; Rescorla, 1982).

With the present experiment, we probed for a similar effect of filler stimuli for sensory attenuation. One widely used method to investigate sensory attenuation is to compare the processing of self-produced and externally produced sounds using electroencephalography (EEG; see Horváth, 2015 for a recent review; for related behavioral findings, see Pfister, Heinemann, Kiesel, Thomaschke, & Janczyk, 2012; Weiss, Herwig, & Schütz-Bosbach, 2011). To replicate basic findings on sensory attenuation, our participants listened to self-produced and externally produced tones while EEG was recorded, and we compared the ERP response for self-produced tones that followed an action immediately (*Motor-Auditory* condition) to the ERP response for externally produced tones (*Auditory* condition). To approach our main question, we introduced two conditions with delayed action effects: In different blocks, the tone followed the participants' button presses either after an unfilled delay of two seconds or after a delay of two seconds which was filled with a visually animated stimulus. For each of these auditory conditions, we assessed the ERP relative to the onset of the tone effect, as well as the participants' agency ratings. In a final control condition, the participants' actions did not cause any tone effects; this non-auditory motor condition served as a baseline to correct for motor-related contributions to the effect-locked ERP (for similar approaches, see e.g., Baess, Horváth, Jacobsen, & Schröger, 2011; Timm, SanMiguel, Keil, Schröger, & Schönwiesner, 2014).

Agency judgements were used as a control measure to confirm the pattern of results described above. We thus expected highest ratings when tones followed actions immediately and lowest for externally produced tones. Ratings for delayed tones should be located in between the ratings of immediate self-produced tones and externally produced tones and, importantly, ratings for tones after filled delays should be higher than ratings for tones after unfilled delays. Following previous suggestions that agency and sensory attenuation are strongly intertwined, we expected smaller (i.e., more attenuated) ERP components for tones after filled delays than for tones after unfilled delays. Furthermore, we expected to find attenuated ERP responses for tones following button presses immediately compared to externally produced tones – i.e., sensory attenuation as shown in previous studies (e.g., Baess et al., 2011; Knolle, Schröger, & Kotz, 2013; Schafer & Marcus, 1973).

Typically, two ERP components are investigated in studies on sensory attenuation: the N1 and the P2 component (Knolle et al., 2013; Lange, 2011; Sowman, Kuusik, & Johnson, 2012; Timm et al., 2014). To analyze sensory attenuation of delayed tones, we focused on the P2 component rather than the N1 component, because the N1 at least partly reflects an orienting response to auditory distraction (Horváth, Winkler, & Bendixen, 2008). Relatedly, N1 suppression effects for self-produced sounds were shown to depend on the inter-stimulus interval, i.e., the time that lies between two sounds. Largest suppression effects for the unspecific N1 component emerged only when the inter-stimulus interval was at least about three seconds long (SanMiguel, Todd, & Schröger, 2013). The P2 component, on the other hand, was not influenced by the inter-stimulus interval in the same study, but reliably suppressed also when the inter-stimulus interval was shorter (SanMiguel et al., 2013). In the present experiment, the inter-stimulus interval differs between conditions because of the delays implemented in some conditions. We, therefore, decided to focus on the P2 component which we predicted to be attenuated when tones follow button presses immediately compared to externally produced tones and, crucially, when self-produced tones follow a filled delay compared to an unfilled delay. Results regarding the N1 component are still reported to allow for comparisons to previous work on sensory attenuation.

2. Method

2.1. *Participants*

Sixteen healthy volunteers were tested (8 males, aged 21–48 years, mean age: 27.56). One participant was left-handed. Based on the effect sizes found in other studies on sensory attenuation (e.g., Baess, Jacobsen, & Schröger, 2008: $d = 1.4$) the sample size of sixteen participants ensured a high power ($1\text{-}\beta > .99$) to detect at least the basic effect of sensory attenuation. All participants gave informed consent prior to the study and received monetary compensation for participation. The study was carried out in accordance with the ethical standards laid down in the Declaration of Helsinki.

2.2. Apparatus *and experimental setup*

Participants sat in an electrically shielded chamber in front of 17″ monitor, with a viewing distance of about 60 cm. They operated the spacebar of the computer keyboard with their left index finger and the mouse with their right hand. The tones stimulus was an 800 Hz marimba MIDI tone of 500 ms duration, which was delivered binaurally through loudspeakers.

Five conditions were presented to all participants (see Fig. 1): (1) *Motor-Auditory*: Tones followed participants' button presses instantly with an action-effect delay of only 50 ms, (2) *Auditory*: Participants listened to externally produced tones, (3) *Delay*: Tones followed after an action-effect delay of 2000 ms, (4) *Filled*: Tones followed after an action-effect delay of 2000 ms which was filled by a visually animated filler stimulus, (5) *Motor*: Participants performed button presses but did not hear any tones.

EEG was recorded using a Brain Vision QuickAmp amplifier with 32 active electrodes (actiCAP; Brain Products, Germany) positioned according to the international 10–20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, TP9, CP5, CP1, CP2, CP6, TP10, P7, P3, Pz, P4, P8, PO9, O1, Oz, O2, PO10). We used average reference to record the EEG signal with a sampling rate of 500 Hz, low-pass filtered at 100 Hz. Additionally, passive electrodes were placed above and below the left eye as well as at the outer canthi of the eyes to record vertical and horizontal electrooculograms (EOGs) to control for eye movements. Impedances were kept below 10 kΩ.

2.3. *Procedure*

In the *Motor-Auditory* condition participants pressed the spacebar to produce the tone. Each trial started with an exclamation point presented in the center of the screen, indicating that the trial commenced. After 500 ms, a white circle appeared beneath the exclamation point. Participants were told that they should press the key after the circle had appeared, but they did not have to react as fast as possible. Each key press predictably triggered an effect tone after 50 ms and the exclamation point and the circle stayed on the screen and disappeared only after tone presentation. The next trial started after an inter-trial interval (ITI) of 1000 ms.

The *Auditory* condition was passive and participants did not have to press a button. Nonetheless, they were asked to look at the screen as in the other conditions. Each trial started with the presentation of an 'X' instead of the exclamation point. After 500 ms, a white circle appeared beneath the 'X' (as in the other conditions). The 'X' and the circle stayed on the screen until after the presentation of the tone. The next trial started after an ITI of 1000 ms. To make the *Auditory*

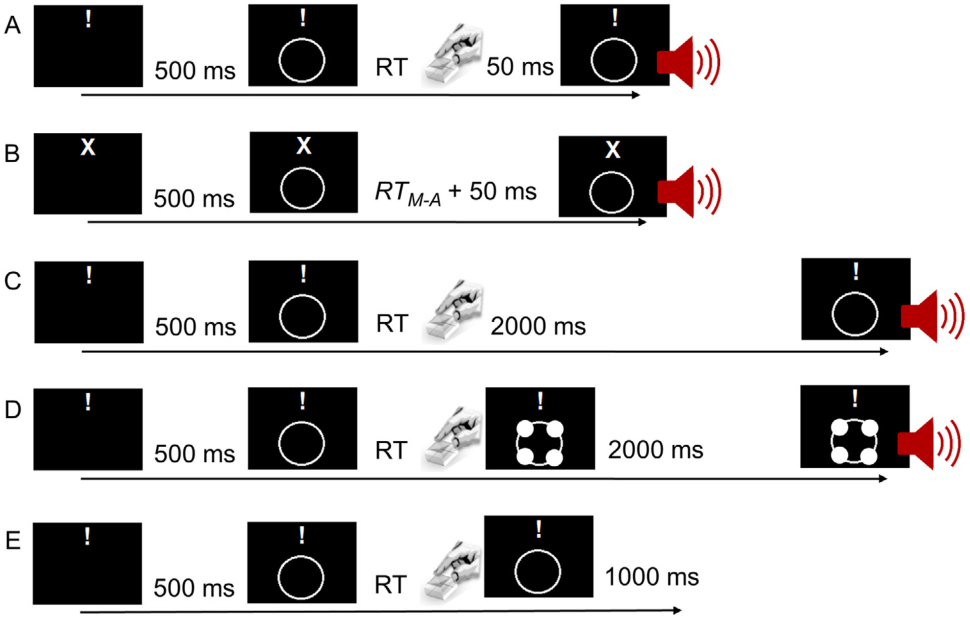

Fig. 1. Trial procedure in all five conditions. **(A) Motor-Auditory**: Each trial started with an exclamation point. After 500 ms, a white circle appeared below the exclamation point, prompting participants to press the spacebar. Reaction time (RT) was defined as the time between appearance of the circle and participants' button press. The button press triggered an effect tone 50 ms later. **(B) Auditory**: Each trial started with an "X", followed by a white circle. The time between circle and tone was set to be identical to the corresponding trial of the Motor-Auditory (M-A) condition, i.e., participants' RT from the Motor-Auditory trial +50 ms. **(C) Delay**: This condition was identical to the Motor-Auditory condition, except that the delay between participants' button press and tone was 2000 ms. **(D) Filled**: This condition was identical to the Delay condition except that in the 2000 ms delay, four small white dots rotated around the circumference of the white circle to fill the interval. **(E) Motor**: This condition was similar to the Motor-Auditory condition but no tone was presented after the participants' button press. Instead, exclamation point and circle stayed on the screen for another 1000 ms after the button press. **Procedural details**: In each condition, the visual stimuli (X/! and circle) stayed on the screen until tone presentation (except Motor where no tone was presented). A black screen was shown for 1000 ms before a new trial started. In conditions A-D, participants were asked to respond to an agency question about the tone on some trials ("How strongly did you feel as causal agent of the tone in the current trial?"); to this end, the question and a visual analog scale appeared after tone presentation.

condition as similar as possible to the *Motor-Auditory* condition, the delay between appearance of the circle and tone was taken from the corresponding trial of the previous *Motor-Auditory* condition (see below for the exact block structure of the experiment). That is to say, from each trial of the *Motor-Auditory* condition the response time (RT; time between presentation of the circle and participant's button press) was saved. For each trial of the *Auditory* condition, the RT of the corresponding trial from the previous *Motor-Auditory* condition was retrieved and 50 ms were added (the time between button press and tone in *Motor-Auditory*). The calculated time was inserted between circle and tone in the current *Auditory* trial.

The *Delay* condition and the *Filled* condition were similar to the *Motor-Auditory* condition except that the effect tone appeared 2000 ms after the action instead of 50 ms. In the *Filled* condition, a visually animated filler stimulus was additionally presented during the 2000 ms delay: Four small white dots appeared on the circumference of the white circle and rotated along the circumference during the delay with a constant angular velocity of 144° per second and stopped rotating with tone presentation.

Finally, in the *Motor* condition, participants were asked to press a key and the setting was similar to the three self-producing conditions. Thus, an exclamation point and a circle appeared on the screen but no tone was presented after the participant's button press. Exclamation point and circle stayed on the screen for another 1000 ms after the button press then disappeared and the screen remained black for 1000 ms of ITI. This condition was used in the analysis to eliminate motor activity.

If participants pressed the button before the circle occurred or if they pressed the button a second time before or during tone presentation, an error message occurred immediately and the next trial started 1000 ms after the error message. In the *Auditory* condition any button press was counted as an error.

The five conditions were presented in mini-blocks of 25 trials each and participants were allowed breaks after each mini-block. We opted for a mini-block structure rather than a trial-to-trial variation to allow participants to adapt to the current delay conditions without taking a considerable toll on working memory (as would have been the case when using five different cues in a trial-to-trial variation). The experiment consisted of 20 mini-blocks, amounting to four mini-blocks per condition. Block order was randomized across participants with the restrictions (1) that all five conditions were presented before repeating a condition and (2) that the *Auditory* condition always directly followed the *Motor-Auditory* condition.

Two times within each mini-block (eight times in total per condition) participants were asked to rate their feeling of agency with respect to the preceding tone. In those trials after presentation of the tone the agency question appeared on the screen: "How strongly did you feel as causal agent for the tone in the current trial?" (German original: *Wie sehr hast du dich in diesem Durchgang als Verursacher des Tones gefühlt?*). At the beginning of the experiment it was made clear to the participants that this question referred to the tone alone and not to the visual effect in the *Filled* condition. Participants were requested to respond on a visual analog scale (VAS) with the left pole labeled '*wenig*' (a little) and the right pole labeled '*sehr*' (a lot). They used the mouse to indicate their response on the VAS which was coded as a score between 0 (left pole) to 100 (right pole). After the participants' response, a black screen was shown for 1000 ms (ITI) and a new trial started. In the *Motor* condition the agency question was not displayed since there was no tone.

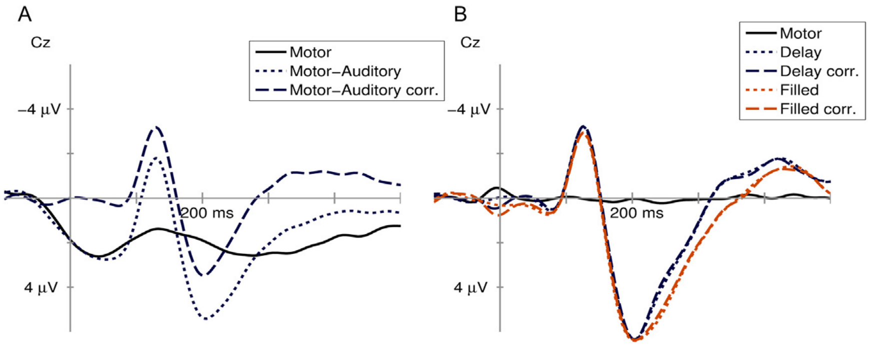

Fig. 2. Mean stimulus-locked ERPs for the electrode Cz, (A) as elicited in the *Motor-Auditory* and the *Motor* condition, accompanied by ERP of the *Motor-Auditory* condition corrected for *Motor* activity (computed as *Motor-Auditory* minus *Motor*) and (B) as elicited in the *Delay*, *Filled* and the *Motor* condition, accompanied by ERP of the *Delay* and *Filled* condition corrected for *Motor* activity (computed as *Delay* minus *Motor* and *Filled* minus *Motor*, respectively). The x-axis represents time in milliseconds (ms) relative to tone onset, the y-axis represents amplitude in microvolts (µV).

2.4. EEG processing

EEG analyses were performed using Matlab (Matworks Inc.) and the Matlab toolbox FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011). We segmented the EEG data into 2000 ms epochs, centered on the tone effect and using a pre-stimulus baseline of 200 ms. Of each condition and block, we excluded the first five trials from the EEG analysis to allow the participants ample time to adapt to the current setting, resulting in a maximum of 80 usable trials per participant and condition. We further excluded all trials containing errors (0.8%).

Data were filtered off-line using a 47.5–52.5 Hz band-stop filter, a 0.1 Hz high-pass filter and a 70 Hz low-pass filter. We performed artifact rejection using the automatic artifact rejection function of FieldTrip based on z-scores (with a threshold of $z = 20$). Data were then corrected for eye movements by performing an independent component analysis and rejecting all components correlating with at least one EOG channel ($r \geq 0.4$). Afterward, data were re-filtered using a 0.1 Hz high-pass filter and a 20 Hz low-pass filter.

ERPs were computed time-locked to tone onset for each participant and condition (*Motor-Auditory*, *Delay*, *Filled* and *Auditory*). To eliminate motor contamination in the *Motor-Auditory* condition, we subtracted ERPs of the *Motor* condition from those in the *Motor-Auditory* condition (see Fig. 2). To this end, we estimated the time of the tone occurrence for the *Motor* condition using the button press-tone-delay of the *Motor-Auditory* condition (i.e., 50 ms). All following figures and analyses use corrected waveforms of the *Motor-Auditory* condition. In the *Delay* and *Filled* conditions we did not conduct any motor correction since the tone occurred 2000 ms after the button press, which allows for natural separation of motor- and tone-related ERPs (see Fig. 2).

2.5. Statistical analyses

For statistical analysis of agency ratings, we conducted a repeated measures analysis of variance (ANOVA) with the within-subject factor Condition (*Motor-Auditory*, *Auditory*, *Delay*, *Filled*).

The analysis window for mean amplitudes of the P2 component was determined in two steps: First, we computed the peak time of the P2 in the grand average of all participants and conditions (excl. *Motor*) in the interval from 150 to 250 ms after tone onset for the electrode Cz, where suppression effects are found to be maximal (e.g., Loehr, 2013; SanMiguel et al., 2013). The actual analysis window was set to the resulting peak time (202 ms) ± 20 ms. Similarly, the N1 peak was defined as the most negative amplitude of the grand average in the interval 50 to 150 ms after tone onset, and the analysis window corresponded to this time (126) ± 20 ms. As attenuation effects in the auditory domain are typically found over the vertex (e.g., Lange, 2011; Schafer & Marcus, 1973; Timm et al., 2014), we evaluated the differences in N1 and P2 for a 2 × 3 fronto-central electrode grid (consisting of the electrodes F3, Fz, F4, C3, Cz, and C4). In a first analysis, we conducted a repeated measures ANOVA with the within-subject factors Condition (*Motor-Auditory*, *Auditory*, *Delay*, *Filled*), Centrality (frontal [F3, Fz, F4], central [C3, Cz, C4]) and Laterality (left [F3, C3], middle [Fz, Cz], right [F4, C4]) on the mean amplitudes of N1 and P2. Greenhouse-Geisser corrections were applied if the assumption of sphericity was violated, and we report corrected p-values along with original degrees of freedom in these cases. Significant interaction effects were further broken down by additional repeated measures ANOVAs with a reduced number of factors.

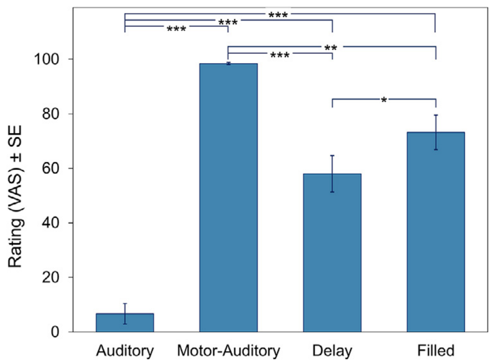

Fig. 3. Mean agency ratings on a visual analog scale (VAS) as a function of condition. Error bars show standard errors of the mean. Brackets and asterisks indicate significance levels of two-tailed paired t-tests.
$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Finally, RTs were analyzed by means of a repeated measures ANOVA with the within-subject factor Condition (comprised of the levels *Motor-Auditory*, *Delay*, *Filled* and *Motor*). We further conducted two-tailed paired t-tests for follow-up comparisons between conditions.

3. Results

3.1. Agency judgements

Fig. 3 shows the mean agency ratings for each condition. Because of errors in the trials with agency judgements, for three participants only seven judgements (instead of eight) were available for one condition each.

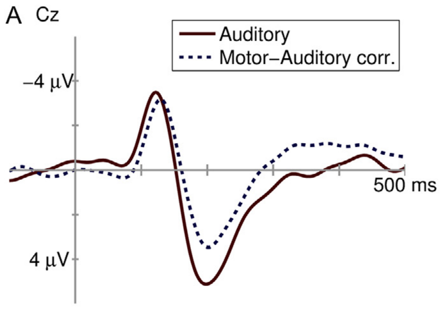

Fig. 4. Mean stimulus-locked ERPs for the electrode Cz. The corrected *Motor-Auditory* curve represents the mean amplitude in the *Motor-Auditory* condition corrected for motor activity (see also Fig. 2). The x-axis represents time in milliseconds (ms) relative to tone onset, the y-axis represents amplitude in microvolts (µV).

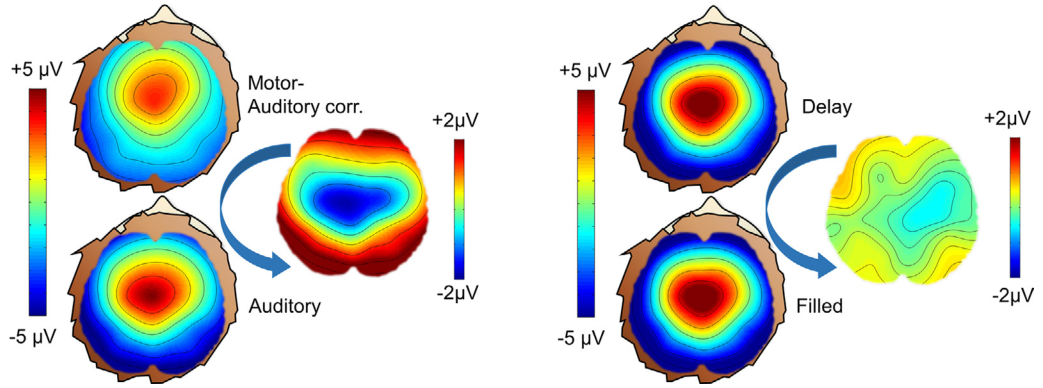

Fig. 5. Scalp maps showing the mean amplitude in a 40 ms window centered on the mean time to peak of the P2 component across conditions (202 ± 20 ms). Difference maps were computed as *Motor-Auditory* (corrected) minus *Auditory*, and *Delay* minus *Filled*, respectively. The corrected *Motor-Auditory* scalp map represents the mean amplitude in the *Motor-Auditory* condition corrected for motor activity (see also Fig. 2).

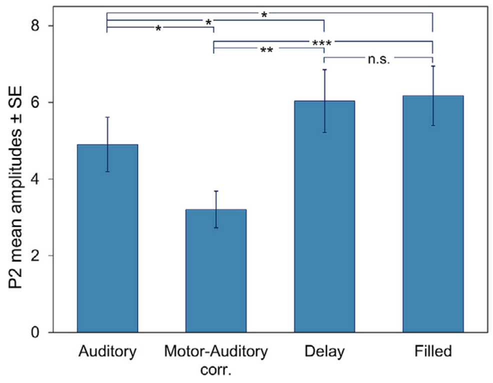

Fig. 6. P2 mean amplitudes (in µV) for the electrode Cz. Error bars represent standard errors of the mean. Brackets and asterisks indicate significance levels of two-tailed paired *t*-tests.
*$p < .05$, ** $p < .01$, *** $p < .001$, n.s. = nonsignificant.

Statistical analysis showed a significant main effect of condition, $F(3,45) = 79.94$, $p < .001$, $\eta_p^2 = .84$. Agency judgements were higher in the *Motor-Auditory* condition ($M = 98.4$; $SE = 0.4$) than in the *Auditory* condition ($M = 6.7$, $SE = 3.8$), $t(15) = 24.51$, $p < .001$, $d = 6.13$, and agency judgments were higher in the *Filled* condition ($M = 73.2$; $SE = 6.3$) than in the *Delay* condition ($M = 58.0$; $SE = 6.7$), $t(15) = 2.57$, $p = .021$, $d = 0.64$.

Furthermore, agency judgements in the *Motor-Auditory* condition were higher than in the *Delay* condition, $t(15) = 5.96$, $p < .001$, $d = 1.49$, and in the *Filled* condition, $t(15) = 4.01$, $p = .001$, $d = 1.00$. In the *Auditory* condition, participants rated agency to be lower than in both, the *Delay* and the *Filled* condition, $t(15) = 7.28$, $p < .001$, $d = 1.82$, and $t(15) = 10.44$, $p < .001$, $d = 2.61$, respectively.

3.2. ERP data

Mean stimulus-locked ERPs of all four conditions for the electrode Cz are presented in Fig. 4 (for the mean stimulus-locked ERPs of the entire electrode grid, see Figs. A1 and A2 in the Appendix). Mean amplitudes for each combination of Condition, Centrality, and Laterality are also shown in the Appendix.

3.2.1. P2 component

Fig. 5 shows scalp maps to illustrate the central distribution of the P2 component. Analysis of P2 mean amplitudes measured in the range from 182 to 222 ms showed a main effect of Condition, $F(3,45) = 3.85$, $p = .028$, $\eta_p^2 = .20$ ($\varepsilon = 0.73$), indicating suppression effects, as well as a main effect of Centrality, $F(1,15) = 18.37$, $p = .001$, $\eta_p^2 = .55$, and a main effect of Laterality, $F(2,30) = 28.90$, $p < .001$, $\eta_p^2 = .66$ ($\varepsilon = 0.67$). The analysis also showed a Condition × Centrality interaction, $F(3,45) = 17.94$, $p < .001$, $\eta_p^2 = .55$ ($\varepsilon = 0.55$), a Centrality × Laterality interaction, $F(2,30) = 27.25$, $p < .001$, $\eta_p^2 = .65$, as well as a significant three-way interaction, $F(6,90) = 3.69$, $p = .003$, $\eta_p^2 = .20$. The Condition × Laterality interaction did not reach significance, $F(6,90) = 1.48$, $p = .193$, $\eta_p^2 = .09$.

To further investigate the three-way interaction, we conducted ANOVAs separately for central and frontal electrodes with the within-subject factors Condition (*Motor-Auditory*, *Auditory*, *Delay*, *Filled*) and Laterality (left, middle, right). For frontal electrodes (F3, Fz, F4), the mean amplitude did not differ between Conditions, as neither the main effect of Condition nor the Condition × Laterality interaction reached significance (both $Fs < 1$). Only the main effect of Laterality was significant, $F(2,30) = 20.32$, $p < .001$, $\eta_p^2 = .58$, indicating higher amplitudes for Fz relative to the lateral electrodes. Central electrodes (C3, Cz, C4) showed a main effect of Condition, a main effect of Laterality, indicating higher amplitudes at Cz compared to lateral electrodes, and a Condition × Laterality interaction (all $Fs > 3.38$, $ps < .005$). To further unravel the two-way interaction and analyze the suppression effects between conditions, we evaluated differences in mean amplitudes between conditions for the electrode Cz (see Fig. 6), following previous studies on sensory attenuation (e.g., Baess et al., 2008; Elijah, Le Pelley, & Whitford, 2016; Loehr, 2013; Mifsud, Beesley, Watson, & Whitford, 2016; Oestreich et al., 2015; SanMiguel et al., 2013; Whitford et al., 2011).

Two-tailed, paired *t*-tests showed that P2 amplitudes over Cz were attenuated (less positive) in the *Motor-Auditory* condition as compared to the *Auditory* condition, $t(15) = 2.67$, $p = .017$, $d = 0.67$. In contrast, the difference in P2 mean amplitudes between the *Delay* condition and the *Filled* condition did not approach significance, $t(15) = 0.61$, $p = .551$, $d = 0.15$. P2 mean amplitudes were also attenuated in the *Motor-Auditory* condition relative to the *Delay* condition, $t(15) = 4.23$, $p = .001$, $d = 1.06$, and in the *Filled* condition, $t(15) = 5.15$, $p < .001$, $d = 1.29$. Furthermore, P2 amplitudes were smaller in the *Auditory* condition compared to the *Delay* condition $t(15) = 2.80$, $p = .013$, $d = 0.70$, as well as the *Filled* condition $t(15) = 2.84$, $p = .013$, $d = 0.71$. P2 peak amplitudes were additionally analyzed and yielded the same pattern of results as P2 mean amplitudes (data not reported for reasons of brevity).

3.2.2. *N1 component*

Analysis of N1 mean amplitudes measured in the range from 106 to 146 ms after tone onset showed a main effect of Laterality, $F(2,30) = 9.31$, $p = .005$, $\eta_p{}^2 = .38$ ($\varepsilon = 0.59$) and a Laterality × Centrality interaction, $F(2,30) = 7.44$, $p = .002$, $\eta_p{}^2 = .33$. N1 amplitudes were more pronounced (i.e., more negative) for central electrodes (Fz, Cz) compared to lateral electrodes (F3, F4, C3, C4). Mean amplitudes of the N1 did not differ between conditions, as the main effect of Condition was not significant, $F < 1$, as were all interactions involving this factor, $Fs < 2.30$, $ps > .090$. The main effect of Centrality was not significant, $F < 1$. N1 peak amplitudes were also analyzed and showed the same pattern of results (data not reported for reasons of brevity).

3.2.3. *Exploratory analysis: slow-wave differences between* Delay *and* Filled

Visual inspection of the ERPs in the *Delay* and the *Filled* condition (Fig. 5) suggested differences in a slow-wave drift following the P2 peak.[1] To evaluate this difference, we calculated the mean voltage for the *Delay* and the *Filled* condition in a time window ranging from 250 to 450 ms after tone onset for the electrode Cz and tested the difference between conditions with a two-tailed, paired *t*-test. Mean amplitudes were higher in the *Filled* condition compared to the *Delay* condition, $t(15) = 2.59$, $p = .020$, $d = 0.65$.

3.3. *RTs*

For RT analyses we excluded all trials with errors (0.8%), as well as trials deviating more than 2.5 standard deviations from the corresponding cell mean, calculated separately for each participant and condition (3.5%).

The repeated measures ANOVA with within-subject factor Condition (*Motor-Auditory*, *Delay*, *Filled*, *Motor*) showed a significant main effect, $F(3,45) = 6.24$, $p = .001$, $\eta_p{}^2 = .29$. Participants initiated button presses faster in the *Motor-Auditory* condition ($M = 453$ ms; $SE = 51$) than in the *Delay* condition ($M = 557$ ms; $SE = 65$), $t(15) = 4.01$, $p = .001$, $d = 1.00$, and in the *Filled* condition ($M = 523$ ms; $SE = 63$), $t(15) = 2.20$, $p = .044$, $d = 0.55$. No difference was found between the RTs in the *Delay* condition and the *Filled* condition, $t(15) = 1.40$, $p = .182$, $d = 0.35$.

Furthermore, participants initiated button presses faster in the *Motor* condition ($M = 452$ ms; $SE = 51$) than in the *Delay* condition, $t(15) = 3.37$, $p = .004$, $d = 0.84$. Only marginally significant RT differences were found between the *Motor* condition and the *Filled* condition, $t(15) = 2.04$, $p = .060$, $d = 0.51$. RTs did not differ between the *Motor* condition and the *Motor-Auditory* condition, $t(15) = 0.03$, $p = .980$, $d = 0.01$.

4. Discussion

The present experiment assessed possible commonalities between sensory attenuation and the subjective sense of agency by analyzing the influence of filler stimuli during action-effect delays on both phenomena. To this end, we compared externally produced tones to self-produced tones that followed participants' actions either immediately, after an unfilled delay of two seconds or after a filled delay of two seconds.

In line with previous findings on agency and causality judgements (Shanks, 1989; van Elk et al., 2014), we expected higher agency judgements for immediate tones as compared to delayed tones, and, importantly for the purpose of our study, higher ratings for tones following filled delays relative to unfilled delays. The data clearly support both predictions. Based on the assumption that agency and sensory attenuation are strongly intertwined, we further expected a similar influence of the filler stimulus on sensory attenuation as measured by the amplitude of the P2 component of the ERP. In contrast to our expectation, however, we found no difference between the P2 elicited by tones after filled as compared to unfilled delays.

These findings point towards a partial dissociation of the mechanisms that give rise to sensory attenuation on the one hand and to the sense of agency on the other hand. The observed dissociation might be explained in terms of a differential involvement of predictive and postdictive mechanisms: Whereas sensory attenuation is mainly explained in terms of predictive mechanisms such as internal forward models (e.g., Horváth, 2015), the sense of agency seems to draw also on postdictive mechanisms such as self-attribution (Haggard & Tsakiris, 2009; Synofzik, Vosgerau, & Newen, 2008; Wegner, 2003). The current data further allow for tentative conclusions about which results are likely caused by predictive mechanisms and which results are likely caused by postdictive mechanisms. A first result to consider is the absence of sensory attenuation for both delay conditions. In fact, a comparison to the *Auditory* condition revealed even larger P2 amplitudes for both delay conditions. At first glance, this absence of attenuation might indicate that delayed tones are not anticipated at all during action selection. Alternatively, they might be anticipated during action selection but the corresponding prediction might not be sufficiently precise or stable in time to affect processing after several seconds of delay. The ERP results cannot distinguish between both alternatives, but the RT data clearly support the latter assertion. More precisely, RTs were slower in both delay conditions as compared to the *Motor-Auditory* condition. This finding suggests that the temporal delay between action and effect had indeed been represented during action planning and initiation, replicating recent observations on the processing of action-effect delays (Dignath, Pfister, Eder, Kiesel, & Kunde, 2014; Haering & Kiesel, 2012). This suggests that delayed action effects are anticipated during action planning, as proposed by a predictive mechanism. The absent impact of the filler stimulus on sensory attenuation, by contrast, cannot be explained along these lines. We therefore suggest that the filler effect that has been demonstrated for agency judgments reflects the operation of postdictive processes alone.

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[1] We thank an anonymous reviewer who suggested this analysis.

Imprecise prediction of the effect onset in both delay conditions may also explain why the ERP amplitudes of delayed tones were even higher as compared to externally produced tones. Even though traditional forward models would assume that sensory attenuation derives from an “efference copy” which is generated during action planning and execution (Blakemore, Wolpert et al., 2000; Hughes et al., 2013), recent discussions highlight a critical role of temporal predictability irrespective of whether temporal predictability derives from own actions or other cues in the environment (Baess et al., 2011; Horváth, 2015; Hughes et al., 2013; Lange, 2011). In the present experiment, the onset of externally produced tones was rather predictable due to the visual stimuli even though participants did not trigger the tones themselves. In most other experimental designs in the literature on sensory attenuation, externally produced tones are not cued in any specific way (following the design of Schafer & Marcus, 1973; see also Baess et al., 2008; Knolle et al., 2013). If sensory attenuation was the result of predicted sensory consequences in general (independent of involved motor commands), immediate externally produced tones could elicit lower amplitudes compared to delayed self-produced tones. Even though this explanation seems compelling, some studies show that sensory attenuation in its entirety cannot be explained by mere temporal prediction of sensory consequences (Baess et al., 2008; Lange, 2011; Timm et al., 2014). Additionally, the amplitude difference between delayed tones and externally produced tones may also be explained by assuming that participants in the present *Auditory* condition might have formed discrete intentions to not press a button after cue presentation (in contrast to passively listening to tones without specific intentions). Such intentions are unlikely to occur in more traditional designs where the tone is not preceded by a cue stimulus. It has been proposed that intentional non-acting shares characteristics of intentional acting and that, just as normal actions, non-actions can become associated with action effects (Kühn & Brass, 2010; Kühn, Elsner, Prinz, & Brass, 2009). Along these lines, one could also imagine that non-actions can cause sensory attenuation. When participants form an explicit intention not to act in order to produce an effect, they may predict the sensory consequences of their non-action. This prediction can then be used to attenuate incoming actual feedback. Thus, in the present experiment participants may have formed the discrete intention to not press a button which was associated with the presentation of a tone. Because of the intention not to act, a prediction of the sensory feedback (i.e., the sound of the tone) may have been generated and because of this prediction, even externally produced tones may have been perceived as attenuated. Even though these conclusions cannot be drawn offhandedly, this might be another explanation why the P2 component for externally produced tones was smaller than the P2 component of delayed, but self-produced effect tones. Whether or not these speculations hold true is to be tested empirically.

The mentioned methodological differences between the current *Auditory* condition and corresponding conditions in the literature might also explain why the comparison of self-produced and externally produced tones revealed attenuation of the P2 component but not of the N1 component. As outlined in the introduction, sensory attenuation is most commonly investigated via the N1 and the P2 component, but usage of these components is heterogeneous across different studies (Horváth, 2015). Whereas some studies have analyzed only the N1 component (Baess et al., 2011, 2008; Lange, 2011; Loehr, 2013), other studies have analyzed both components, N1 and P2 (e.g., Knolle et al., 2013; SanMiguel et al., 2013; van Elk et al., 2014), or the peak-to-peak amplitudes from N1 to P2 (Timm et al., 2014). Additionally, functional interpretation of the ERP components is still under debate (Horváth, 2015). Still, the missing N1 attenuation may be a result of the temporal predictability of tones in the *Auditory* condition of the present experiment (in contrast to other experimental designs on sensory attenuation, e.g., Baess et al., 2008; Knolle et al., 2013; Schafer and Marcus, 1973). This predictability may have specifically influenced the N1 component but not the P2 component, as it has been proposed that the N1 component partly reflects an orienting response to auditory distraction (Horváth et al., 2008). A reduction of this component may be interpreted as a reduced orienting response to stimuli (SanMiguel et al., 2013), and orienting responses might have been abolished by the visual cues in the present experiment. Another explanation for the absent N1 attenuation might be the 50 ms delay implemented in the *Motor-Auditory* condition of the present experiment, as it has been proposed that such short delays eliminate N1 suppression in healthy people (at least without training; Aliu, Houde, Nagarajan, 2009; Whitford et al., 2011). Other studies, however, showed sensory attenuation of the N1 component even for delays considerably larger than 50 ms (350 to 750 ms: Lange, 2011; and 200 up to 1000 ms: van Elk et al., 2014). Thus the complete absence of N1 attenuation cannot be explained exclusively by this short delay.

Finally, exploratory analyses revealed that the processing of tones following filled and unfilled delays differed in the time interval following the P2 peak. This differential slow-wave drift might reflect the difference that was found in the judgements of agency. These analyses were conducted post-hoc, however, and should be regarded with caution. The observed drift might also be due to the different visual stimulation, as tones following filled delays were accompanied by the stopping of the rotating visual stimuli. Evidence for sensory attenuation of self-produced visual effects is scarce and contradictory (Mifsud, Oestreich et al., 2016). Reduced visual evoked potentials have been found at the vertex (Gentsch & Schütz-Bosbach, 2011; Hughes & Waszak, 2011), while for occipital areas both reduced (Roussel, Hughes, & Waszak, 2014) and enhanced amplitudes (Hughes & Waszak, 2011; Mifsud, Oestreich et al., 2016) could be found. So far, no final conclusion can be drawn about the impact of the visual differences between both delay conditions. Whether the different processing of tones following filled and unfilled delays after the P2 merely represents an artefact of different visual stimulation or reflects the difference found in the judgements of agency remains to be tested empirically.

5. Conclusion

The present results document a partial dissociation of sensory attenuation and the sense of agency. Whereas filling an action-effect interval did not alter the sensory processing of effects as measured with ERPs, it did increase judgements of agency. This partial dissociation points towards a stronger contribution of postdictive processes to the sense of agency than to sensory attenuation.

Author note

Results reported in this article are part of the first author’s master thesis.

Conflict of interest

The authors declare that there are no conflicts of interest.

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Appendix.

Mean stimulus-locked ERPs of the entire electrode grid (Figs. A1 and A2) and corresponding mean amplitudes (Table A1).

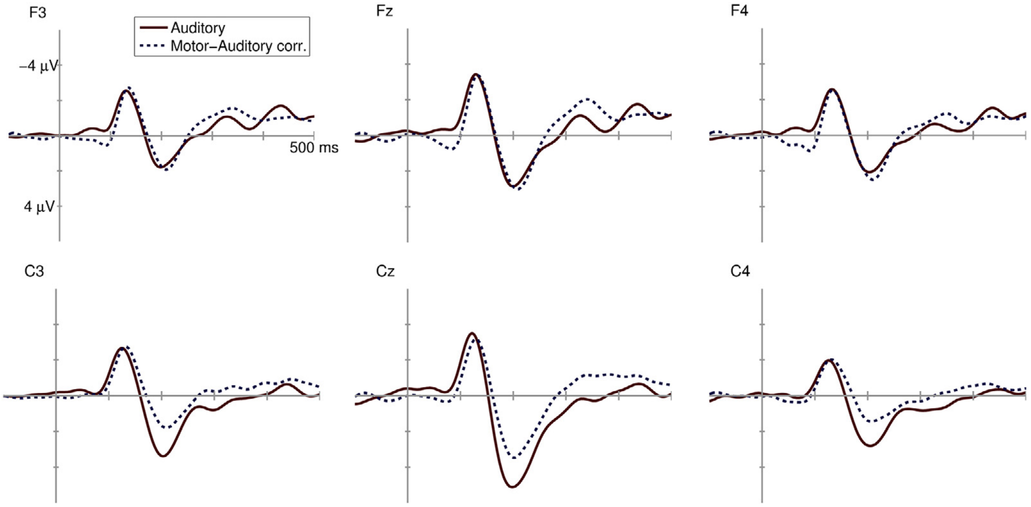

Fig. A1. Mean stimulus-locked ERPs for electrodes F3, Fz, F4, C3, Cz, and C4 as elicited in the *Motor-Auditory* (corrected for motor activity) and the *Auditory* condition. The x-axis represents time in milliseconds (ms) relative to tone onset, the y-axis represents amplitude in microvolts (µV).

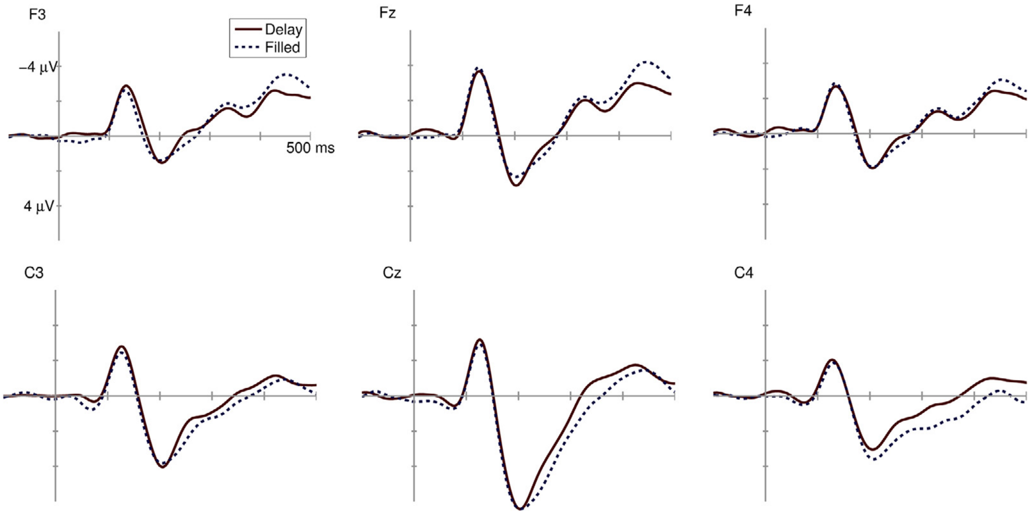

Fig. A2. Mean stimulus-locked ERPs for electrodes F3, Fz, F4, C3, Cz, and C4 as elicited in the *Delay* and the *Filled* condition. The x-axis represents time in milliseconds (ms) relative to tone onset, the y-axis represents amplitude in microvolts (µV).

Table A1
P2 and N1 mean amplitudes (in µV) for each condition and electrode.

	Frontal electrodes			Central electrodes		
P2	F3	Fz	F4	C3	Cz	C4
Auditory	1.61	2.61	1.88	3.12	4.90	2.64
Motor-Auditory	1.56	2.64	2.12	1.52	3.21	1.25
Delay	1.27	2.46	1.64	3.65	6.03	2.81
Filled	1.27	2.14	1.67	3.61	6.17	3.32
N1						
Auditory	−2.09	−2.87	−2.06	−2.29	−2.90	−1.67
Motor-Auditory	−1.89	−2.55	−1.73	−2.25	−2.64	−1.69
Delay	−2.31	−2.99	−2.11	−2.35	−2.54	−1.69
Filled	−2.09	−3.17	−2.23	−2.03	−2.30	−1.48

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