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# Sensory attenuation prevails when controlling for temporal predictability of self- and externally generated tones

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A R T I C L E I N F O

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A B S T R A C T

Sensory attenuation of self-produced, compared to physically identical but externally produced events is a classical finding in research on perception in action. The most prominent model to explain this effect draws on an internal forward model generating predictions about action outcomes, efference copies, during action planning and initiation. Even though this finding has a long tradition in psychology and neuroscience, several studies have highlighted methodological limitations which open the door for alternative explanations of sensory attenuation effects, most notably in terms of temporal prediction. Here we present an experimental design which carefully controls for this confounding factor. Crucially, we observed the auditory N1 component of the event-related potential to be attenuated for self-generated tones as compared to externally generated tones even when a predictive cue (a bar that is continuously filling up) allows for identical temporal predictability of both events. These findings suggest that voluntary actions do indeed involve a unique, predictive component, affecting the perceptual processing of ensuing events.

## 1. Introduction

Perceiving someone else clicking on the top of a ballpoint pen repeatedly can be experienced as being loud and distracting, while the same sound is barely noticed when produced by oneself. This is one of many examples illustrating how our perception can be fooled on a fundamental level – in this case by varying the source of a sensory event. In fact, the phenomenon that effects of one's own voluntary actions are being perceived differently than externally generated sensory events has been observed in many modalities and is commonly consolidated under the term of sensory attenuation (Hughes et al., 2013). The precise mechanisms underlying these findings, however, are still unclear.

Classical accounts attribute sensory attenuation to motor-related prediction mechanisms (Miall and Wolpert, 1996; Roussel et al., 2013; von Holst and Mittelstaedt, 1950; Wolpert et al., 1995). According to such "internal forward models", the cognitive system computes a prediction of the upcoming effects of a voluntary movement (the "efference copy"), against which the actual sensory input is compared. In theory, only mis-matches between predicted and actual sensory events are processed further. These models thus reserve a unique role of motor actions for sensory attenuation, as efference copies can only be compiled in the presence of a motor plan.

This basic assumption has been challenged by several empirical observations over the last decade, which suggested that similar attenuation effects can be found when events predictably follow other cues than voluntary actions (Bendixen et al., 2009; Sato, 2008; Schröger et al., 2015; but compare Desantis et al., 2012). In the face of such evidence, it is crucial to determine whether sensory attenuation for motor actions exceeds the effect of non-motor predictions to evaluate models that reserve a prominent spot for the former mechanism (Hughes et al., 2013). The present study aimed to contribute to the state of the field by specifically addressing the role of temporal prediction. This factor has been a major confound in many previous designs where the timing of self-generated effects tended to be more predictable than the timing of externally generated effects as we will discuss in the following.

Sensory attenuation is often measured via auditory event related potentials (ERPs, for a review see Horváth, 2015), where the effect is reliably observed as a reduction in N1 and P2 amplitude of the ERP when comparing self-generated to externally generated tones (e.g., Schafer and Marcus, 1973; Timm et al., 2014).[1] In these studies,

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[1] We will focus on the auditory modality in this context because attenuation effects are typically more reliable and robust as compared to visual stimuli (Schwarz et al., 2018).

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participants typically press a key which instantly triggers a tone, whereas for externally generated events, the computer plays the same tone with variable intervals while the participant listens passively to these stimuli. When comparing self-generated and externally generated tones in this setup, any potential differences in N1 or P2 amplitude might thus either result from the unique involvement of motor-related forward models, or these differences may alternatively result from the high predictability of self-generated as compared to externally generated tones. That is, while forward models only draw on predictions made on the basis of motor plans, mere temporal predictability irrespective of one's own efferent activity can explain the classical results equally well.

To approach the role of temporal predictability for sensory attenuation, Bäß et al. (2008) introduced conditions with unpredictable action-effect delays. They indeed observed larger attenuation for self-generated tones when action-effect delays were predictable than when they were not, suggesting that temporal predictability affects the processing of self-generated sounds. However, in this study high predictability was implemented via immediate effects (i.e., without action-effect delay) whereas low predictability was implemented by inserting an action-effect delay of 500–1000 ms. Potential effects of temporal predictability could thus also be attributed to the impact of different delays (Weller et al., 2017). Lange (2011), by contrast, found the ERP of self-generated tones to be attenuated compared to visually cued ones but did not undertake a comparison to unpredictable tones. While these studies seem to suggest that self-generated tones might indeed be attenuated even when compared to predictable externally generated tones, other researchers have reported more ambiguous findings. Ford et al. (2007), for instance, addressed temporal prediction for externally generated tones by presenting a visual countdown from three to one (shown as the corresponding number of dots for 500 ms each) and playing the tone together with the last display. This procedure resulted in a small but significant effect of temporal prediction as compared to uncued presentation of externally generated tones. While this makes a good case for the influence of temporal prediction, it does not inform about an additional impact of the tones' origin (self or external). However, the same study also featured an experiment, in which the classical comparison of self- vs. externally generated tones (not including a countdown) was assessed. A cross-experimental analysis over all conditions of the two experiments suggested a small, marginally significant attenuation of self- compared to externally generated tones going beyond mere predictability. Other studies, by contrast, have found no differences at all between auditory ERPs comparing predictable self-generated and equally predictable externally generated tones (Dogge et al., 2018; Kaiser and Schütz-Bosbach, 2018). These experiments differed from the typical protocol, however, by studying reactions to visual stimuli rather than the self-initiated actions used in previous research.

Taken together, the current state of the field does not seem to allow for clear conclusions about whether or not sensory attenuation for self-generated stimuli entails a unique, motor-related component. That is, the question of whether motor planning and initiation contributes specific predictions cannot be resolved by the current database. We aim to resolve this ambiguity, by contributing novel sensory attenuation data in a design that (a) contrasts self-generated with externally generated tones with perfectly controlled predictability while (b) employing uncued, self-initiated actions in the self-generated condition. Finally, we aimed to compare the results of this design to the classic setup in which unpredictable tones are compared to self-generated tones following immediately after self-initiated button-presses.

## 2. Material and methods

### 2.1. Participants

We collected data of 24 voluntary participants at the University of Würzburg. Data of one participant had to be excluded due to technical malfunction during data acquisition. Based on effect sizes from previous studies, the remaining sample size ensured a power of more than 0.99 to detect the classic attenuation effect on the N1 component (a minimum of 10 participants would be needed for a power of 0.9 for the effects reported in previous work; Bäß et al., 2008; Lange, 2011; Timm et al., 2014). The remaining 23 participants (15 female) were aged 30.65 years on average (SD = 9.25) and all but one were right-handed. Participants signed an informed consent form prior to the experiment and received compensation in form of payment or partial course credit.

### 2.2. Apparatus

Participants sat in an electrically shielded, dimly lit room at 60–70 cm viewing distance from a 17″ stimulus presentation screen. Written instructions were presented on the screen and any questions were clarified by the experimenter on demand. Procedure and stimulus presentation was programmed using E-Prime 2.0. Keyboard actions were performed on a standard QWERTZ-keyboard with the right index finger on the key 'K'. The sound stimulus, a single marimba tone (500 ms duration; Musical Instrument Digital Interface tone), was presented via headphones (see the supplementary material for the audio file and a spectral characterization of the tone). EEG activity was recorded from 32 active ActiCap electrodes (Brain Products, Gilching, Germany) against average reference and was re-referenced off-line to linked mastoids. Participants were fitted with an elastic cap, that aided electrode positioning according to the international 10–20 system (recorded electrodes: Fp1, Fp2, AFz, F7, F3, Fz, F4, F8, FC1, FCz, FC2, T7, C3, Cz, C4, T8, TP9, CP1, CP2, TP10, P7, P3, Pz, P4, P8, PO9, O1, Oz, O2, PO10, M1, and M2). Additionally, two bipolar electrodes were installed on the outer canthi of both eyes and above and below the left eye to record a vertical and a horizontal Electrooculogram (vEOG and hEOG). All impedances were kept below 10 kΩ at the beginning of recording (see Winkler et al., 2013, for common practices regarding auditory ERPs). EEG was recorded with a sampling rate of 512 Hz.

### 2.3. Procedure

To allow for a random ordering of the experimental blocks, externally produced tones did not consist of a replay of voluntary blocks (as is sometimes implemented in the literature) but inter-sound intervals (ISIs) were jittered around a fixed value, taken from a pilot-experiment (2750 ± 650 ms; see Appendix A for the analysis). Additionally, participants completed a short session to train the timing of their button presses before starting the main experiment.

The experiment itself consisted of five block types which were all presented five times to each participant in random order (see Fig. 1). Three of those closely followed the design of previous studies on the subject (Bäß et al., 2008; Schafer and Marcus, 1973) whereas two additional block types were introduced between which predictability of self- and externally generated tones was kept constant.

**Self No Delay (Self-ND)**. Participants pressed the button, thereby generating a tone, which was presented without delay after the button press.

**External No Delay (External-ND).** Externally generated tones were

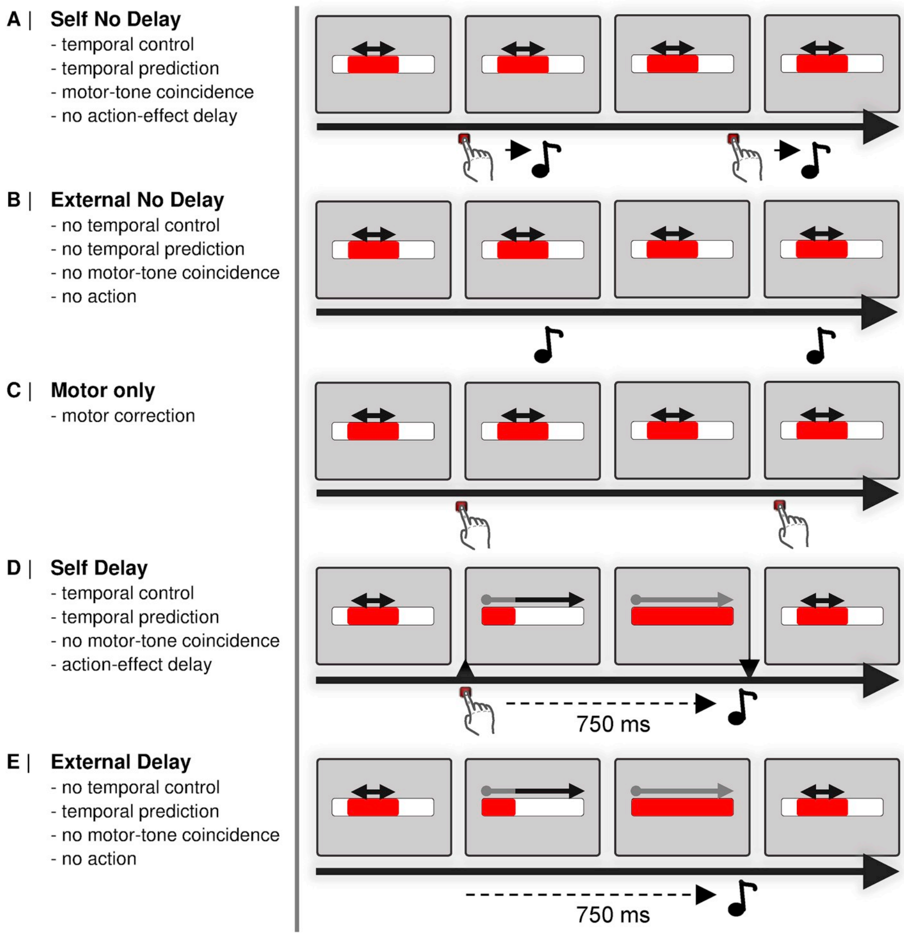


**Fig. 1.** Trials procedure in all five conditions. **A** | Self No Delay (Self-ND). Participants generated a tone instantaneously with each button press. **B** | External No Delay (External-ND). Externally generated tones were presented to the participant without precueing. **C** | Motor only (M). Participants performed button presses without generating any tones **D** | Self Delay (Self-D). Participants generated a tone by their key-press but the tone was presented only after a delay of 750 ms during which a loading bar filled up. **E** | External Delay (External-D). Tones were externally generated and played with a random inter-sound interval; 750 ms before tone onset, a loading bar started to fill up and the tone was presented at the moment it was filled completely.

presented with a random ISI (2100–3400 ms) and the participants' task was to merely listen to these tones.

**Motor only (M).** Participants periodically pressed the key but did not generate a tone by their actions.

**Self Delay (Self-D).** Participants pressed the key and generated a tone by it. The tone was presented after a delay of 750 ms during which a loading bar was presented. This loading bar indicated the onset of the tone which was played at the exact moment the loading bar was filled completely.

**External Delay (External-D).** Tones were generated externally with random ISIs (2100–3400 ms) but 750 ms prior to their onset, a loading bar started to continuously fill up and the tone was presented at the exact moment the loading bar was filled completely.[2]

During the whole experiment, whenever no loading bar was presented, a comparable visual stimulus moved back and forth on the screen to keep visual stimulation constant at all times. In all active blocks (Self-ND, Self-D, M), that is all blocks in which the participant was asked to perform a button press, a warning symbol ('!') appeared whenever the interval between button presses was smaller than 2000 ms. These trials were not entered into the analysis. Blocks consisted of 25 trials each and after each block participants were given the opportunity to take a short break. After active blocks, the mean ISI was displayed and participants were encouraged to improve it (closer to 2750 ms).

### 2.4. Data treatment

We excluded the first 5 trials of each block to remove any artifacts due to uncertainty about the present condition. Additionally, any trials following an ISI smaller than 2000 ms were removed from further analysis (2.2% of all active trials). After exclusion of short ISIs, participants kept intervals of 2833 ms on average between their button presses, thus differing less than 100 ms from mean intervals in computerized blocks (2754 ms).

### 2.5. EEG preprocessing

EEG data were processed in Matlab (Mathworks Inc.) using FieldTrip (Oostenveld et al., 2011). Data were segmented into 2000 ms epochs with a pre-stimulus baseline of 200 ms, centered on the tone for all conditions in which a tone was presented (Self-ND, External-ND, Self-D, External-D). The motor correction condition (Motor only) was analyzed time locked on the button press (M0) as well as centered on 750 ms after button press (M750) for each trial. This procedure was chosen to correct both, the Self-ND as well as the Self-D condition for possible motor artifacts (for a critical assessment of such correction methods, see Horváth et al., 2018; Neszmélyi and Horváth, 2017). As a consequence of the overlapping epochs of M0 and M750, conditions were divided into two clusters (Cluster 1: Self-ND, External-ND and M0; Cluster 2: Self-D, External-D and M750) and all following preprocessing steps were executed separately for each cluster. Artifact rejection was performed by the automatic artifact reject function of FieldTrip that

[2] The delay was chosen to provide sufficient time for the participants to use the cue effectively while at the same time aiming to minimize the action-effect delay to still allow for action-related attenuation effects (Lange, 2011; van Elk et al., 2014; Weller et al., 2017).

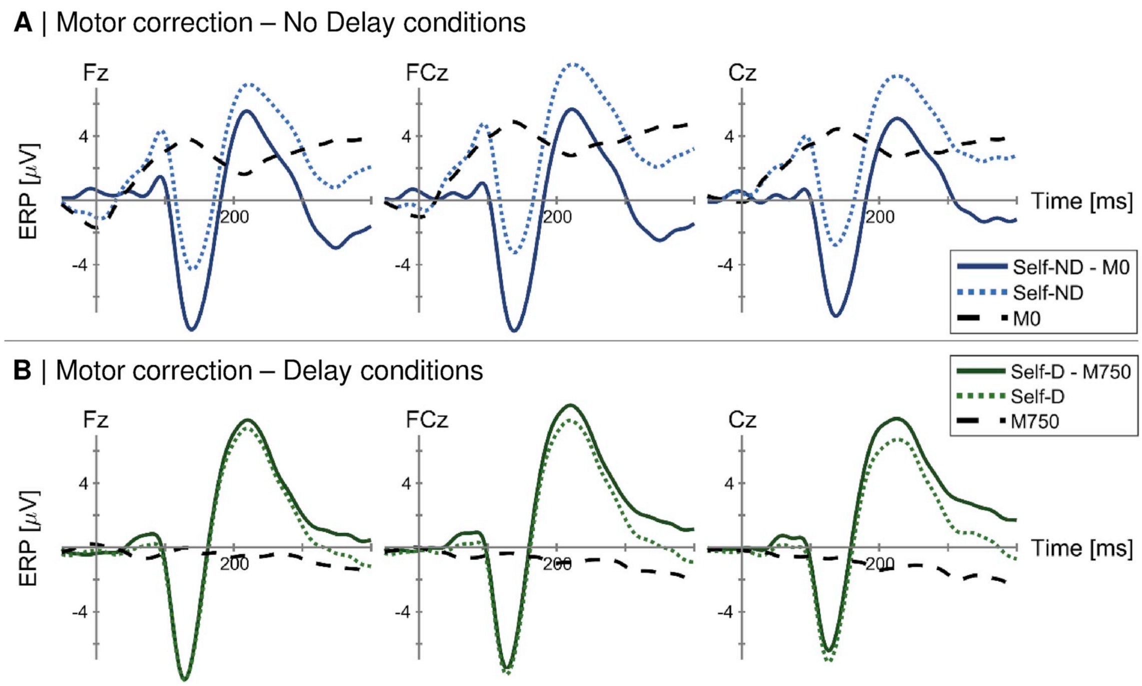


**Fig. 2.** Uncorrected and motor-corrected ERP waves of the self-produced conditions time locked on the tone and corresponding ERP wave of the motor only condition at electrodes Fz, FCz and Cz for **A** | Self No Delay condition (Self-ND; self-generated tones without action-effect delay) with M0 (ERP of the motor only condition time locked on the button press) and **B** | Self Delay condition (Self-D; self-generated tones with 750 ms action-effect delay filled with a predictive loading bar) with M750 (ERP of the motor only condition time locked on 750 ms after the button press).

uses z-scores to define artifacts (threshold of z = 20). Ocular artifacts were removed by the means of an independent component analysis that identified all correlations of components with the EOG channels. All components correlating with at least one EOG channel ($r \geq 0.4$) were rejected. Electric hum had previously been filtered out by a 47.5–52.5 Hz band-stop filter and as a last step data was filtered with a 0.1 Hz high-pass and 70 Hz low-pass filter. For plotting, data was re-filtered with a 20 Hz low-pass filter.

### 2.6. ERP analysis

The trials of each condition were pooled individually for each participant and each electrode. The Self-ND and Self-D condition were motor-corrected by subtracting the amplitudes of the Motor only condition at the appropriate time (Self-ND – M0; Self-D – M750, see Fig. 2). Hereafter, Self-ND and Self-D refer to the motor-corrected amplitudes of the conditions.

Although N1 and P2 waveforms are often measured at the vertex, a more frontal peak can be found for the N1 when inter-sound intervals (ISIs) are below 4 s (Vaughan and Ritter, 1970). Therefore, all analyses were conducted for the frontal midline electrodes Cz, FCz and Fz. As the N1 component usually peaks at around 100 ms after stimulus onset, the respective analysis window for mean amplitude was defined around the point of maximal sensory attenuation over all electrodes and conditions between 50 ms and 150 ms after stimulus onset. The specific point of analysis relating to the N1 component was determined by averaging all data over participants and computing the points of maximal difference between the no delay (External-ND, Self-ND) and the delay conditions (External-D, Self-D) on all three considered electrodes (119 ± 20 ms; marked as a grey area on Fig. 3). Correspondingly, the search window for the P2 component was set from 150 to 250 ms after stimulus onset and the related mean potential for the P2 component was computed exactly as described above (197 ± 20 ms after stimulus onset, also marked as a grey area on Fig. 3).

## 3. Results

The grand-averaged ERP waveforms on electrodes Fz, FCz and Cz are plotted in Fig. 3A for no delay (Self-ND, External-ND) and delay conditions (Self-D, External-D). All waves show the classic form of an auditory ERP with a clear negative potential in the range of the N1 component and a positive potential in the range of the P2 component. Fig. 3B shows corresponding topographical plots that depict the activity differences for the two no-delay conditions and for the two delay conditions, respectively. Data of the N1 and P2 component were analyzed separately and we entered the respective mean amplitudes into a 3 (Electrode [Fz | FCz | Cz]) * 2 (Design [No-Delay | Delay]) * 2 (Control [Self | External]) within-subjects analysis of variance (ANOVA). Whenever Mauchly's test indicated that sphericity could not be assumed, degrees of freedom (*df*s) were corrected using the method of Greenhouse-Geisser. In the following we always report the uncorrected *df*s with the adjustment coefficient ε and the corrected test-statistics. Significant results were followed up by two-way ANOVAs and *t*-tests tailored to the hypotheses. We only report relevant statistics in the text and provide the detailed results in Appendix B.

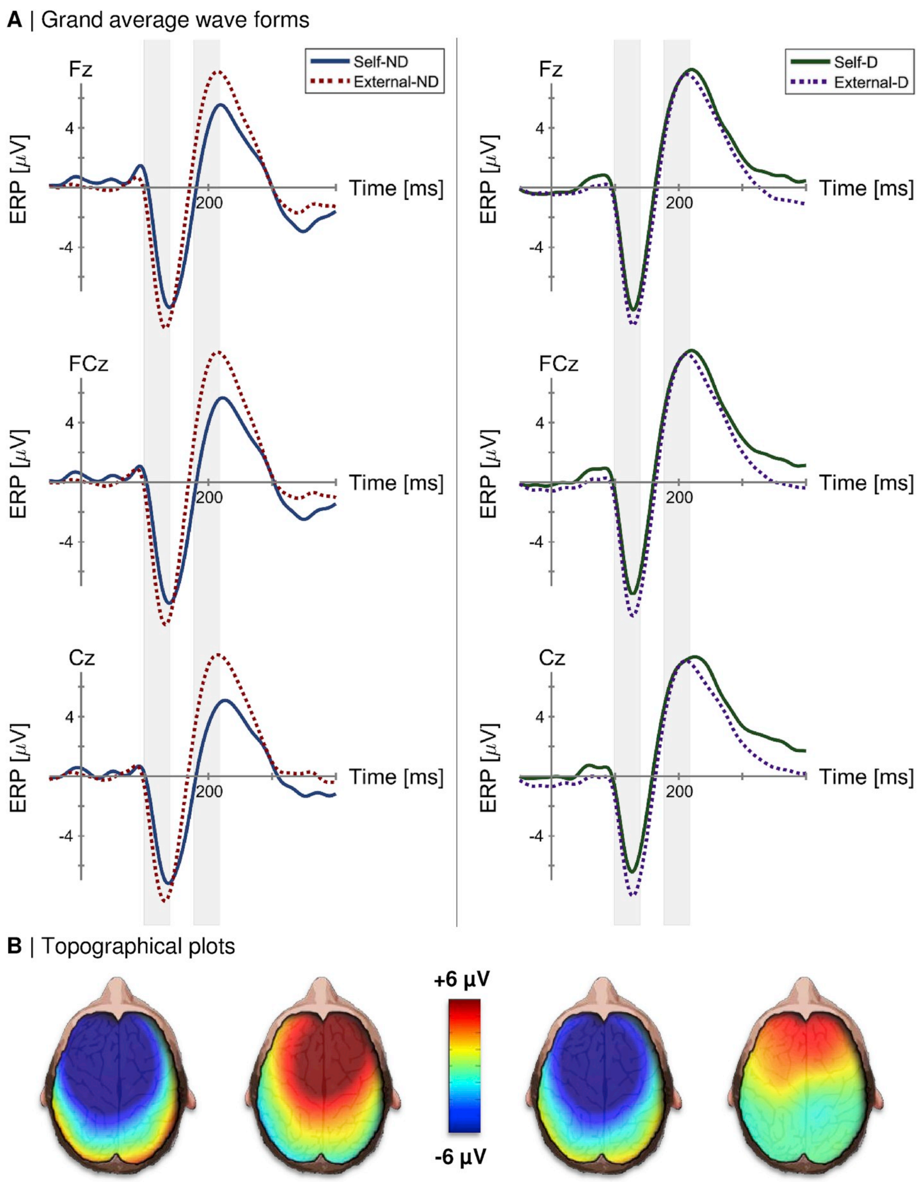


**Fig. 3. A** | Grad average, tone-locked ERPs for the No Delay and the Delay condition, separated by electrode. Grey areas mark the analysis windows for components N1 (119 ± 20 ms) and P2 (197 ± 20 ms). **Self No Delay (Self-ND):** Self-generated tones without action-effect delay; **External No Delay (External-ND):** Externally produced, unpredictable tones; **Self Delay (Self-D):** Self-generated tones with 750 ms action-effect delay filled with a predictive loading bar; **External Delay (External-D):** Externally produced, temporally predictable tones that are preceded by a 750 ms loading bar. **B** | Topographical plots depicting the difference of potentials between the two No Delay conditions (External-ND – Self-ND, left pair) and between the two Delay conditions (External-D – Self-D, right pair) at the specific time points for component N1 (119 ± 20 ms, respective left plot) and component P2 (197 ± 20 ms, respective right plot).

### 3.1. N1 (99–139 ms)

Fig. 4 shows mean N1 amplitudes for all experimental conditions. The omnibus ANOVA revealed a main effect of control, $F(1,22) = 23.40$, $p < .001$, $\eta_p^2 = 0.52$, with more negative amplitudes for externally generated as compared to self-generated tones as well as a main effect of electrode, $F(2,44) = 7.71$, $p = .009$, $\eta_p^2 = 0.26$, $\varepsilon = 0.55$. There was a three-way interaction of control x design x electrode, $F(2,44) = 5.36$, $p = .019$, $\eta_p^2 = 0.20$, $\varepsilon = 0.69$, which we followed up by separate two-way ANOVAs for each electrode. All ANOVAs showed a significant effect of control (all *ps* < .001, all $\eta_p^2$s > 0.46), while a main effect of design only reached significance on electrode Fz, $F(1,22) = 6.68$, $p = .017$, $\eta_p^2 = 0.23$. The two factors did not interact on either electrode (all *ps* > .144). Paired *t*-tests revealed significant differences between Self-ND and External-ND amplitudes on all three electrodes, Fz, $t(22) = 3.64$, $p = .001$, $d = 0.76$, FCz, $t(22) = 3.20$, $p = .004$, $d = 0.67$, and Cz, $t(22) = 2.63$, $p = .015$, $d = 0.55$. Crucially, the delay conditions (Self-D vs. External-D) also differed significantly at electrode FCz, $t(22) = 2.39$, $p = .026$, $d = 0.50$, and Cz, $t(22) = 2.90$, $p = .008$, $d = 0.60$, whereas there was a non-significant trend for electrode Fz, $t(22) = 1.65$, $p = .113$. To further compare whether the attenuation effects differed between the delay and the no delay conditions – i.e., whether predictability (design) had an influence on the sensory attenuation effect – we additionally compared the difference between no delay conditions and delay conditions (e.g. (External-ND – Self-ND) vs. (External-D – Self-D)). This comparison did not show a significant effect on Fz, $t(22) = 1.51$, $p = .144$, $BF_{01} = 2.54$, FCz, $t(22) = 0.89$, $p = .386$, $BF_{01} = 3.20$, or Cz, $t(22) = 0.42$, $p = .681$, $BF_{01} = 4.22$.[3] Bayes Factors provide tentative evidence in favor of equality of conditions.

### 3.2. P2 (177–217 ms)

Fig. 5 shows mean P2 amplitudes for all experimental conditions. The ANOVA revealed a main effect of control, $F(1,22) = 13.6$, $p = .001$, $\eta_p^2 = 0.38$, design, $F(1,22) = 15.87$, $p < .001$, $\eta_p^2 = 0.42$, and electrode, $F(2,44) = 5.62$, $p = .020$, $\eta_p^2 = 0.20$, $\varepsilon = 0.61$. We found a significant three-way interaction, $F(2,44) = 4.36$, $p = .039$, $\eta_p^2 = 0.17$,

[3] We computed Bayes Factors in favor of the null hypothesis of equality of conditions ($BF_{01}$). We used the BayesFactor package for R (version 0.9.12–4.2) and assumed a medium scale parameter for the prior distribution. We interpret $BFs_{01} \geq 3$ as statistical evidence in favor of the null hypothesis.

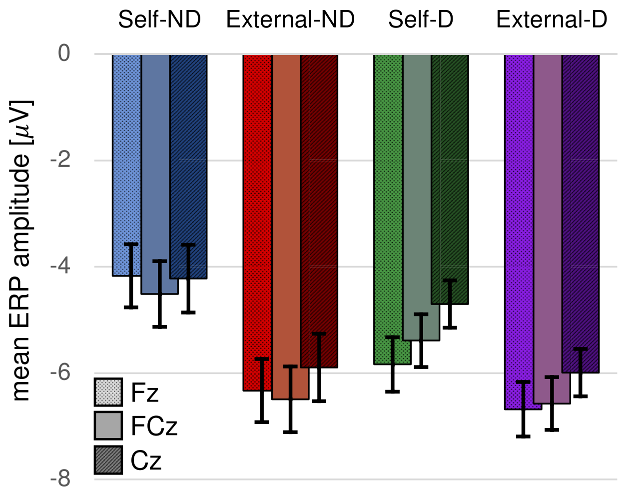


**Fig. 4.** Mean amplitudes of the N1 component (99–139 ms after tone onset), at electrodes Fz, FCz, and Cz. Error bars show $SE_{PD}$ (Pfister and Janczyk, 2013; Self-ND vs External-ND; Self-D vs. External-D) separately for each electrode. Self-ND: Self No Delay; External-ND: External No Delay; Self-D: Self Delay; External-D: External Delay.

ε = 0.62, and again followed-up on this result with three separate 2x2 ANOVAs. All three analyses showed a main effect of control (all *ps* < .011, all $\eta_p^2$s > 0.26), and design (all *ps* < .005, all $\eta_p^2$s > 0.31) as well as a two-way interaction (all *ps* < .001, all $\eta_p^2$s > 0.44). The effects will be further analyzed by paired *t*-tests. A pairwise comparison of self- with externally produced tones was significant on all electrodes for the no delay conditions (all *ps* < .001, all *ds* > 0.86) while self- and externally generated tone amplitudes did not differ on any electrode for the delay conditions (all *ps* > .647, all $BFs_{01}$ > 4.14). Again, we compared these effects between no delay and delay conditions to test for an influence of predictability on the sensory attenuation effect. This comparison was significant on all electrodes: Fz, $t(22) = 4.23$, $p < .001$, $d = 0.88$, FCz, $t(22) = 5.79$, $p < .001$, $d = 1.21$, and Cz, $t(22) = 5.88$, $p < .001$, $d = 1.23$.

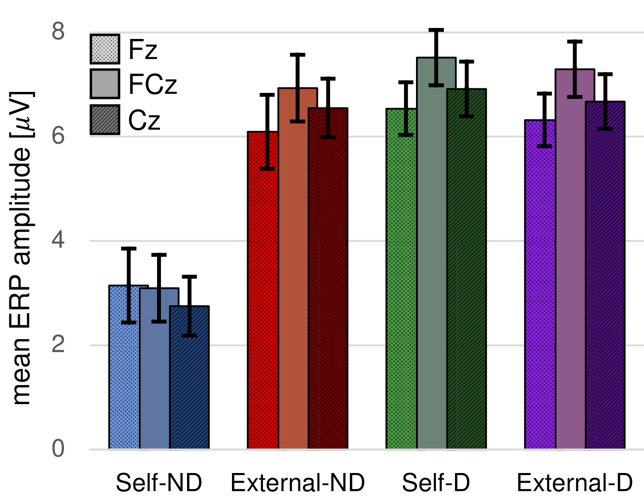


**Fig. 5.** Mean amplitudes of the P2 component (177–217 ms after tone onset), at electrodes Fz, FCz, and Cz. Error bars show $SE_{PD}$ (Pfister and Janczyk, 2013; Self-ND vs External-ND; Self-D vs. External-D) for each electrode. Self-ND: Self No Delay; External-ND: External No Delay; Self-D: Self Delay; External-D: External Delay.

## 4. Discussion

The experiment aimed to study sensory attenuation for self-generated relative to externally generated tones when both conditions are closely matched for temporal predictability through a visual cue. We did indeed observe sensory attenuation at the N1 component for this comparison, suggesting that self-generated actions incorporate a unique, self-related mechanism, which attenuates the ensuing action effects. Following typical forward models, this unique function likely reflects the operation of low-level motor prediction. Alternatively, or in addition, this effect may also have a higher-level, cognitive basis in the perceived control over an event (Desantis et al., 2012). Either way, both alternatives go beyond accounts in terms of mere temporal predictability.

We further expected the attenuation effects of this matched comparison to be smaller than the attenuation effects of the classical comparison of immediate, self-generated tones to unpredictable externally generated tones. Contrary to this hypothesis, we found no modulation of the attenuation effect at the N1 component. However, the expected effect did show at the P2 component. Our data thus adds to the literature suggesting distinct features of the auditory ERPs N1 and P2 component (e.g., Crowley and Colrain, 2004). Specifically, the absence of an attenuation effect at the P2 component when predictability was held constant, which is in line with previous findings (Sowman et al., 2012), might be considered grounds for new hypotheses to disentangle the functional correlates of these neural markers. Specifically, these findings may be interpreted as a close link of attenuation observed at the N1 component to motor-related processes while attenuation at the P2 peak is contingent upon mere predictability of events. Whether or not this implies multiple, distinct attenuation effects or rather that different aspects of sensory attenuation are reflected in different ERP components is not clear at this point and warrants additional research. Moreover, conclusions regarding the absence of effects at the P2 component should be treated with caution as the present sample size was not optimized for documenting support for a null hypothesis of no difference between conditions.

To shed further light on the influence of temporal delay on the sensory attenuation effect, we performed a post-hoc comparison of self-produced tones with and without action-effect delay (i.e., the Self-D and Self-ND conditions).[4] Studies without predictive visual cues in the action-effect interval have repeatedly shown that such delays have a lasting impact not only on sensory attenuation (e.g., Weller et al., 2017), but also on related measures such as temporal binding (e.g., Haggard et al., 2002) or the motivation from control effect (Eitam et al., 2013; Karsh et al., 2016). For N1, paired *t*-tests comparing Self-ND with Self-D could not give a clear indication regarding the impact of our delay (750 ms) on mean ERPs. Data shows significantly smaller amplitudes for the Self-ND condition on electrode Fz, $t(22) = 2.71$, $p = .013$, $d = 0.56$, while statistics on electrode FCz are inconclusive, $t(22) = 1.37$, $p = .184$, $BF_{01} = 2.01$, and amplitudes at electrode Cz are indicated to be equal, $t(22) = 0.78$, $p = .445$, $BF_{01} = 3.48$. At component P2 however, comparisons on all electrodes clearly indicate smaller amplitudes for the Self-ND condition (all *ps* < .001, all *ds* > 0.90). Note, that these statistics should be treated with some caution, as the study did not primarily aim to show the impact of delay and thus the design is not optimally suited for this comparison. Namely, the conditions do not only differ in delay but also slightly in visual stimulation. Nevertheless, the results permit speculations regarding the influence of a delay between button press and tone or, respectively, the influence of motor-tone coincidence. A more pronounced ERP-response after a delay, at least on the P2 component, may imply that the relation between the action and its effect is diminished when time passes in between. However, this observation also seems to mirror findings

[4] We thank an anonymous reviewer for this suggestion.

suggesting that ERPs to tones might be attenuated solely because they coincide with a button press independently of any action-effect associations (Horváth, 2013, 2015), suggesting that conditions without action-effect delay may overestimate the impact of predictability on sensory attenuation effects (Weller et al., 2017). The present delay conditions, by contrast are less susceptible to confounds regarding action-effect coincidence, so that our results indeed indicate a unique influence of control over on the processing of the event in question.

Of course our data do not necessarily imply that the observed attenuation effects are best explained by internal forward models. Indeed, the findings can be similarly explained on a cognitive level, as in control expectations, or by ideomotor accounts which assume that effect anticipations are functionally relevant already for action planning and initiation (e.g., Hommel, 2009; Horváth, 2015; Kunde, 2001; Müsseler & Hommel, 1997; Pfister, 2019). Ideomotor accounts would thus assume that it is not the prediction that results from an action plan but, in contrast, that the action results from the anticipation of upcoming effects. Thus, while our study demonstrates a classic sensory attenuation effect of self- compared to externally produced tones despite equal predictability, pinpointing the precise mechanism underlying this effect will require further, carefully controlled experiments to disentangle the multitude of potential influences that give rise to the phenomenon of sensory attenuation.

## Declaration of interest

The authors declare no financial or personal conflicts of interest. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Preregistration and data availability

This study has been preregistered prior to data collection via the Open Science Framework prereg challenge form. The preregistration as well as preprocessed data are available at https://osf.io/zv8cc/.

## CRediT authorship contribution statement

**Annika L. Klaffehn:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Project administration, Writing - original draft, Visualization. **Pamela Baess:** Conceptualization, Writing - review & editing. **Wilfried Kunde:** Conceptualization, Supervision, Writing - review & editing. **Roland Pfister:** Conceptualization, Methodology, Software, Formal analysis, Supervision, Project administration, Writing - original draft.

## Appendix A. Analysis of the pre-experiment

Over the course of a small pre-study, five participants each completed five blocks of the Self No Delay, Self Delay and the Motor only conditions with 25 trials per block. Participants were instructed to keep the time between the button presses at 2.5–3 s. Just as in the main experiment, they underwent the button press speed training beforehand and heard the generated tone if that was part of the block. This pre-experiment was implemented to adjust the random inter-sound intervals (ISIs) to the intervals produced by participants and to identify potential major problems with keeping the button press speed constant beforehand. With all trials included (n = 1800), participants generated average ISIs of 2614 ms (SD 752 ms) and, more crucially, when trials witch ISIs ≤ 2000 (11.5%) were excluded from analysis (n = 1593), participants achieved an almost perfect mean ISI of 2743 ms (SD 685 ms). Random ISIs in the main experiment were therefore set as averagely 2750 ± 650 ms.

## Appendix B. Test statistics

Table B1
N1 component, three-way ANOVA (control x design x electrode)

| | *F* | $df_{test}$ | $df_{error}$ | *p* | $\eta_p^2$ | ε |
|---|---|---|---|---|---|---|
| control | 23.40 | 1 | 22 | < .001 | 0.52 | |
| design | 2.42 | 1 | 22 | .134 | 0.10 | |
| electrode | 7.71 | 2 | 44 | .009 | 0.26 | 0.55 |
| control x design | 0.90 | 1 | 22 | .354 | 0.04 | |
| control x electrode | 0.17 | 2 | 44 | .745 | 0.01 | 0.65 |
| design x electrode | 14.35 | 2 | 44 | < .001 | 0.39 | 0.66 |
| control x design x electrode | 5.36 | 2 | 44 | .019 | 0.20 | 0.69 |

*Note.* Tests statistics for the three-way ANOVA (control x design x electrode) of the N1 component. ε is only reported when sphericity could not be assumed (based on Mauchly's test).

Table B2
N1 component, two-way ANOVAs (control x design) for each electrode

| | | *F* | $df_{test}$ | $df_{error}$ | *p* | $\eta_p^2$ |
|---|---|---|---|---|---|---|
| Fz | control | 19.02 | 1 | 22 | < .001 | 0.46 |
| | design | 6.68 | 1 | 22 | .017 | 0.23 |
| | control x design | 2.29 | 1 | 22 | .144 | 0.09 |
| FCz | control | 21.87 | 1 | 22 | < .001 | 0.50 |
| | design | 1.47 | 1 | 22 | .238 | 0.06 |
| | control x design | 0.78 | 1 | 22 | .386 | 0.03 |
| Cz | control | 22.82 | 1 | 22 | < .001 | 0.51 |
| | design | 0.57 | 1 | 22 | .458 | 0.03 |
| | control x design | 0.17 | 1 | 22 | .681 | 0.01 |

*Note.* Tests statistics for the three two-way ANOVAs (control x design) of the N1 component separated by electrode (Fz, FCz, Cz).

Table B3
N1 component, paired *t*-tests

| | | $t$ | $df$ | $p$ | $d$ | $BF_{01}$ |
|---|---|---|---|---|---|---|
| Fz | Self-ND vs. External-ND | 3.64 | 22 | .001 | 0.76 | |
| | Self-D vs. External-D | 1.65 | 22 | .113 | 0.34 | 1.41 |
| | Δ No-Delay vs. Δ Delay | 1.51 | 22 | .144 | 0.32 | 1.70 |
| FCz | Self-ND vs. External-ND | 3.20 | 22 | .004 | 0.67 | |
| | Self-D vs. External-D | 2.39 | 22 | .026 | 0.50 | |
| | Δ No-Delay vs. Δ Delay | 0.89 | 22 | .386 | 0.18 | 3.20 |
| Cz | Self-ND vs. External-ND | 2.63 | 22 | .015 | 0.55 | |
| | Self-D vs. External-D | 2.90 | 22 | .008 | 0.60 | |
| | Δ No-Delay vs. Δ Delay | 0.42 | 22 | .681 | 0.09 | 4.22 |

*Note.* Tests statistics for all paired *t*-tests of the N1 component. $BF_{01}$: Bayes Factor in favor of equality of conditions. $BF_{01}$ is only given when the *p*-value of the *t*-test exceeded 0.1.
Self-ND: Self No Delay; External-ND: External No Delay; Self-D: Self Delay; External-D: External Delay; Δ No-Delay: Self-ND – External-ND; Δ Delay: Self-D – External-D.

Table B4
P2 component, three-way ANOVA (control x design x electrode)

| | $F$ | $df_{test}$ | $df_{error}$ | $p$ | $\eta_p^2$ | $\varepsilon$ |
|---|---|---|---|---|---|---|
| control | 13.60 | 1 | 22 | .001 | 0.38 | |
| design | 15.87 | 1 | 22 | < .001 | 0.42 | |
| electrode | 5.62 | 2 | 44 | .020 | 0.20 | 0.61 |
| control x design | 30.16 | 1 | 22 | < .001 | 0.58 | |
| control x electrode | 3.03 | 2 | 44 | .083 | 0.12 | 0.65 |
| design x electrode | 3.04 | 2 | 44 | .086 | 0.12 | 0.61 |
| control x design x electrode | 4.36 | 2 | 44 | .039 | 0.17 | 0.62 |

*Note.* Tests statistics for the three-way ANOVA (control x design x electrode) of the P2 component. ε is only reported when sphericity could not be assumed (based on Mauchly's test).

Table B5
P2 component, two-way ANOVAs (control x design) for each electrode

| | | $F$ | $df_{test}$ | $df_{error}$ | $p$ | $\eta_p^2$ |
|---|---|---|---|---|---|---|
| Fz | control | 7.74 | 1 | 22 | .011 | 0.26 |
| | design | 9.94 | 1 | 22 | .005 | 0.31 |
| | control x design | 17.93 | 1 | 22 | < .001 | 0.45 |
| FCz | control | 14.68 | 1 | 22 | < .001 | 0.40 |
| | design | 17.78 | 1 | 22 | < .001 | 0.45 |
| | control x design | 33.52 | 1 | 22 | < .001 | 0.60 |
| Cz | control | 17.75 | 1 | 22 | < .001 | 0.45 |
| | design | 18.33 | 1 | 22 | < .001 | 0.45 |
| | control x design | 34.53 | 1 | 22 | < .001 | 0.61 |

*Note.* Tests statistics for the three two-way ANOVAs (control x design) of the P2 component separated by electrode (Fz, FCz, Cz).

Table B6
P2 component, paired *t*-tests

| | | $t$ | $df$ | $p$ | $d$ | $BF_{01}$ |
|---|---|---|---|---|---|---|
| Fz | Self-ND vs. External-ND | 4.15 | 22 | < .001 | 0.86 | |
| | Self-D vs. External-D | 0.43 | 22 | .672 | 0.09 | 4.21 |
| | Δ No-Delay vs. Δ Delay | 4.23 | 22 | < .001 | 0.88 | |
| FCz | Self-ND vs. External-ND | 6.00 | 22 | < .001 | 1.25 | |
| | Self-D vs. External-D | 0.42 | 22 | .681 | 0.09 | 4.23 |
| | Δ No-Delay vs. Δ Delay | 5.79 | 22 | < .001 | 1.21 | |
| Cz | Self-ND vs. External-ND | 6.75 | 22 | < .001 | 1.41 | |
| | Self-D vs. External-D | 0.46 | 22 | .647 | 0.10 | 4.15 |
| | Δ No-Delay vs. Δ Delay | 5.88 | 22 | < .001 | 1.23 | |

*Note.* Tests statistics for all paired *t*-tests of the P2 component. $BF_{01}$: Bayes Factor in favor of equality of conditions. $BF_{01}$ is only given when the *p*-value of the *t*-test exceeded 0.1.
Self-ND: Self No Delay; External-ND: External No Delay; Self-D: Self Delay; External-D: External Delay; Δ No-Delay: Self-ND – External-ND; Δ Delay: Self-D – External-D.

## Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2019.107145.

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