I, You, Robot: Attenuation for auditory outcomes of actions performed by different agents shows distinct patterns for N1 and P2 amplitudes

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I, You, Robot: Attenuation for auditory outcomes of actions performed by different agents shows distinct patterns for N1 and P2 amplitudes

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ABSTRACT

Compared to external tones, previous studies found reduced N1 and P2 amplitudes in event-related potentials not only for self-generated tones, referred to as sensory attenuation, but also for tones generated by a person the participant observed. The P2 in this situation was attenuated, even when accounting for temporal predictability. P2 attenuation has also been related to the judgement of agency, which refers to explicit agency attribution. To test whether the P2 attenuation in action observation depends on the attribution of agency to a human agent, we added conditions with robotic hands performing the tone-eliciting action. Therefore, we compared N1 and P2 amplitudes of tones generated by an observed action of another person using either their own or a robotic hand, and by the computer shown as a robotic hand, with those of unpredictable external tones. Only N1 amplitudes in action observation with a human agent (human or robotic hand) were significantly attenuated compared to unpredictable external tones, while the N1 for the different observation conditions did not differ from each other. The P2 was attenuated for all action-observation conditions compared to unpredictable external tones, while again the amplitudes of the action-observation conditions did not differ from each other. Thus, while the threshold for N1 attenuation during action observation may be reached only if a human is observed, the P2 showed attenuation effects irrespective of agency attribution. This contrasts with previous findings for the P2 suggesting agency-related effects. Future research could further examine the modulation of attenuation by the action-observation setting.

Sensory attenuation (SA) was defined as a reduction in the perceptual or neurophysiological response to stimuli that are self-generated compared to external stimuli that are otherwise identical (for reviews see Dogge et al., 2019; Hughes et al., 2013; Kiepe et al., 2021). For the auditory modality that means perceiving self-generated tones as less loud and having reduced neurophysiological responses to self-generated tones compared to identical external tones. The latter is reflected in reduced amplitudes of the event-related potential (ERP) components N1 and P2, which are typically analysed in studies on auditory SA applying electroencephalography (EEG; Horváth, 2015; Kiepe et al., 2021).

SA has traditionally been explained by forward model predictions of the sensory input based on the efference copy of the motor command (Wolpert & Flanagan, 2001). Because this would make SA specific to self-generation, SA has been suggested to be an implicit measure of the sense of agency (Hughes et al., 2013; Kiepe et al., 2021), that is, the sense of being the cause of an action and its outcome (Gallagher, 2000; Synofzik et al., 2008). Indeed, neurophysiological SA (N1, P2, and

N1-P2 complex) was found to occur only for voluntary as opposed to involuntary action (Jack et al., 2021; Timm et al., 2014). In the forward model framework, the cerebellum has been identified as a relevant brain structure for both motor-to-somatosensory (e.g., Blakemore et al., 2001) and motor-to-auditory predictions: For neurophysiological SA in the auditory modality, N1 attenuation was absent in cerebellar patients but P2 attenuation was intact (Knolle et al., 2013), suggesting a functional dissociation between the two components, with only the N1 reflecting forward model predictions. Beyond this dissociation, forward models do not suffice to explain all SA-related phenomena reported in the literature: For instance, attenuation of N1 and P2 has also been described without a contingent action-effect relation (e.g., Horváth et al., 2012), N1 attenuation was found even without action (e.g., Harrison et al., 2021), and the typically rapid learning of arbitrary action-effect associations has been suggested to speak against forward model mechanisms (Dogge et al., 2019). Instead, it has been suggested that a combination of different mechanisms produces neurophysiological SA (Dogge et al.,

2019; Horváth, 2015; Hughes et al., 2013). According to accounts claiming that SA can be explained by general predictive mechanisms, a similar attenuation of neurophysiological activity might occur for predictable external tones relative to unpredictable ones as for self-generated tones (Dogge et al., 2019; Kiepe et al., 2021; Korka et al., 2022). Findings regarding this are mixed, but some studies have indeed found such attenuation for the N1 (e.g., Harrison et al., 2021) and the P2 (e.g., Schafer & Marcus, 1973).

Regarding the relationship between SA and the sense of agency, a better understanding may be gained when differentiating between the feeling of agency, which refers to an implicit self-agency experience, and the judgement of agency, which refers to explicit attribution of agency to oneself (Synofzik et al., 2008; Synofzik et al., 2013). Sensorimotor prediction was proposed to contribute to the feeling of agency (e.g., Synofzik et al., 2013). Concerning the judgement of agency, it was proposed that the feeling of agency itself as well as other (contextual) information contribute to this more explicit agency attribution (Synofzik et al., 2008; Synofzik et al., 2013). For neurophysiological SA, sensorimotor prediction mechanisms are likely indexed by the N1 component, which might thus reflect the feeling of agency. More general, context-dependent mechanisms (e.g., beliefs, contextual cues) have been associated with modulations of the P2, which might be interpreted as reflecting a more retrospective agency judgement (e.g., Seidel et al., 2021; Timm et al., 2016). Some insights seem to come from studies on patients with schizophrenia, a disorder associated with impaired agency attribution (Franck et al., 2001). In these studies, N1 attenuation has been found to be reduced in patients with schizophrenia compared to healthy controls (Ford & Mathalon, 2012) and N1 attenuation has been correlated with agency misattribution in this population (Heinks-Maldonado et al., 2007). These findings can be interpreted as suggesting that altered sensorimotor prediction mechanisms, as reflected by reduced N1 attenuation, affect the implicit self-agency experience, which in turn alters the attribution of agency to the self. However, evidence from healthy individuals did not indicate significant relations between anomalous perception and either the N1 or the P2 (Egan et al., 2023). Moreover, most studies on schizophrenic patients have focused on the N1 component, leaving the role of the P2 component unexplored. In our previous studies, we found P2 attenuation not only for self-generation but also for action observation and interpreted this as reflecting the judgement component of an extended sense of agency, that is, the explicit attribution of agency to another person (Egan et al., 2023; Ghio et al., 2021; Ghio et al., 2018). Rather than a sense of whether oneself was the agent behind this sensory input, it would describe a sense of whether there was an (intentional) agent behind it.

Action observation is similar to self-generation not only in terms of attribution to an agent but also to some extent in brain activation (for reviews regarding the mirror neuron system see Ferrari & Rizzolatti, 2014; Iacoboni, 2009). In the forward model framework, it was proposed that the mirror neuron system, and the action simulation it might entail, enables motor-based predictions also for observed action-outcomes, similar to the process for self-generation (Wolpert et al., 2003). As such, SA might be extended to other-generated tones.

Previous SA studies in action observation provided mixed results. Perceptual SA was reported to be both present (Sato, 2008) and absent (Weiss et al., 2011) in studies applying similar experimental paradigms, with a potential modulation by the participants' individualism (i.e., a cultural dimension; Cao & Gross, 2015). Concerning neurophysiological SA, N1 attenuation for tones elicited by observed actions, which might reflect a forward-model driven vicarious feeling of agency (i.e., the feeling of authorship over an observed action and its outcome; Wegner et al., 2004), was only found with sufficient delay between action and outcome (Ghio et al., 2021; Ghio et al., 2018). A recent study further found no amplitude difference between cued tones and tones generated by observed actions (Egan et al., 2023), suggesting a central role of temporal predictability for the N1 attenuation (cf. Harrison et al., 2021),

although it does not exclude mirror neuron mechanisms as potential source of predictions during action observation. The P2, on the other hand, was consistently attenuated in action observation (Egan et al., 2023; Ghio et al., 2021) and the attenuation was stronger than for tones that were visually cued without action observation (Egan et al., 2023). The same study also showed that the P2 for cued tones was attenuated relative to un-cued, and thus unpredictable, tones. The P2 thus seems to reflect in part predictability and in part agency attribution. For the latter, contextual information is likely taken into account, as is the case for self-related judgement of agency. Thus, even if the N1 attenuation reflects a vicarious feeling of agency, the context allows the attribution of agency to an observed person rather than oneself in analogy to self-other distinction during empathic processes (Lockwood, 2016). However, the cue and the observation conditions in our previous study (Egan et al., 2023) differed not only in the attribution of the tone to a human agent, but also in the action-effect association, which was lacking in the cue condition. If the action-effect association rather than agency attribution to a human led to the stronger P2 attenuation in action observation, then this would relate to attribution of causality rather than agency attribution as the mechanism underlying P2 attenuation.

In the present study, we further investigated whether neurophysiological SA, represented by the N1 and particularly the P2, reflects agency attribution, with a focus on action observation. We did this by extending the previously applied paradigm (Egan et al., 2023) with two additional action-observation conditions, in which the button press was performed by a robotic hand: In one condition the robotic hand was said to be controlled by another person and in the other by the computer. Unlike the cue condition, both conditions included an action-effect association. For strict control of the timing, all action-observation conditions were implemented using videos presented onscreen. To our knowledge, the only study using robotic stimuli in a study on (perceptual) SA in the auditory modality was Sato (2008). In this study, tones generated by a robotic arm were not attenuated compared to external tones, but tones that were self-generated or generated by an observed person were attenuated compared to the robot condition, thus suggesting that the agency attribution to a human agent, being predictable and intentional, is relevant (Sato, 2008). Because our focus was on attenuation in action observation, for the main analyses, we considered only the three action-observation conditions (human agent and human hand, human agent and robotic hand, computer agent and robotic hand) and the condition with unpredictable external tones. Results including two more conditions with self-generated tones and visually cued tones, respectively, are reported in the Supplement (Statistical Analyses for All Conditions).

Although the relation between perceptual and neurophysiological measures is unclear (e.g., Palmer et al., 2016), we nevertheless expected to find lower P2 amplitudes for tones that were generated by another human agent compared to those without a human agent and to un-cued external tones (Egan et al., 2023; Ghio et al., 2021). Furthermore, we expected P2 attenuation for tones not generated by human agents, but which were yet temporally predictable, compared to the condition with unpredictable ones (Egan et al., 2023). Because some studies suggested that the N1 attenuation solely relates to the temporal predictability of the tone (e.g., Harrison et al., 2021), we expected N1 attenuation for all action-observation conditions. Additionally, we acquired explicit measures of agency (i.e., judgement and confidence rating) to examine their influence on P2 amplitudes (cf. Sato, 2008; Timm et al., 2016). While the first judgement of who the agent was served as an instruction check, the agency-confidence rating might be related to the degree of attenuation for conditions with intentional agents (i.e., self-generation, human and human-robot action observation). Potential uncertainties would likely reflect uncertainties regarding the distinction between an observed person and the computer due to the technical component of the tone generation rather than the distinction between an observed person and oneself.

In additional analyses, we considered the modulation of the attenuation effects by certain individual traits of the participants measured via questionnaires. In previous studies, delusional ideation or anomalous perception was hypothesised to affect SA (Cao & Gross, 2015; Egan et al., 2023) and so we included the Cardiff anomalous perceptions scale (CAPS; Bell et al., 2006). Given its relation to the mirror neuron system (Iacoboni, 2009; but see Lamm & Majdandzic, 2015), empathy has been considered as a modulatory variable for SA in action observation (Cao & Gross, 2015; Egan et al., 2023), and so we also assessed the short form of the empathy quotient (EQ; Wakabayashi et al., 2006). The potential SA for tones generated by a robotic arm might further be modulated by the participants' tendency to anthropomorphise it. According to Epley et al. (2007), this tendency could be increased, for instance, by higher perceived similarity in motion and morphology, and possibly by individualism. Therefore, we included the anthropomorphism questionnaire (AQ; Neave et al., 2015). Participants with higher AQ scores might process the robotic action-observation conditions more similarly to the human action-observation condition than participants with lower scores. Lastly, we assessed the general attitudes towards robots scale (GAToRS; Koverola et al., 2022) to account for potential biases of participants. For instance, if participants have stronger negative attitudes, they might selectively anthropomorphise the robotic hand less than they would other objects (and show less attenuation).

1. Methods

1.1. Sample

To further investigate N1 and P2 attenuation for tones that were generated by an observed action we aimed to recruit a sample of similar size as in previous related studies. In two previous studies involving action observation, 36 (Ghio et al., 2018) and 38 participants (Ghio et al., 2021) were tested, respectively. The P2 attenuation effect for tones that were self-generated, generated by another participant, or visually cued (Egan et al., 2023) that we aimed to explore further was found based on data from 49 participants. In the current study, we acquired 49 healthy right-handed participants in total. However, nine participants were excluded from analysis because the data of one experimental block was missing (two due to technical difficulties, seven due to task-irrelevant button presses, i.e., not following instructions for that block). Therefore, the analysed sample consisted of 40 participants (10 male). The mean age was 23.63 years (SD = 4.88; range: 18–40). Before beginning the experiment participants gave written informed consent. They received up to 25 Euro or course credit for participation. As recruitment was primarily conducted at the university, the sample consisted mostly of students. The ethics committee of the Faculty of Mathematics and Natural Sciences at Heinrich Heine University Düsseldorf has approved this study.

1.2. Experimental design and conditions

Based on the contingent paradigm (Horváth, 2015) and our previous studies that adapted the paradigm for action observation (Egan et al., 2023; Ghio et al., 2021; Ghio et al., 2018; Seidel et al., 2023), we included the self-generation and external-tone conditions as well as conditions with action observation and a condition in which a visual cue preceded the tone. However, the primary focus was on the action-observation and the external-tone conditions. The latter represents the comparison condition to which SA was determined in previous studies (Horváth, 2015). Our study comprised three action-observation conditions: (1) Observation of button presses performed by a human agent (see Ghio et al., 2018; Seidel et al., 2023), and (2) observations of button presses performed by a robotic hand that was controlled by another person or (3) by a computer. While all three of these conditions contained the action-outcome association, only the first two conditions featured agency attribution to another person, and only the first

condition provided the human-likeness that was consistent with action-observation conditions of previous studies. Thus, we explored whether the neurophysiological SA we previously found for action observation (Egan et al., 2023; Ghio et al., 2021; Ghio et al., 2018; Seidel et al., 2023) is modulated by the attribution of agency to another person, while accounting for a possible effect of human-likeness (i.e., human versus robotic depiction).

For all conditions but the external-tone condition, there was an experimental block and an additional control block. In the experimental blocks, tones were time-locked to a preceding event, that is, a self-performed action, an observed action, or a visual cue. In the respective control block, the event took place without the presentation of tones. The purpose of these control blocks was to calculate the difference between the ERPs of events with and events without tones, and thus correct for activity elicited by the preceding event, an (observed) action and/or visual stimuli, and thus unrelated to the tone (cf. motor correction in the contingent paradigm; Horváth, 2015). The experimental design is visualised in Fig. 1.

1.2.1. Action-observation and external conditions

To determine SA, tone processing in the (corrected) condition of interest (where the correction is the result of the difference of experimental and control blocks) is typically compared to tone processing in the external-tone condition (Horváth, 2015). In the external condition, the interval between the tones was determined by a function that picked a random number from a normal distribution with a mean of 2400 ms and a standard deviation of 350 ms (overall, for the analysed sample: M = 2425 ms, SD [across participant means] = 44 ms). Participants were instructed to listen to the tones. A picture of the response box was shown on the computer screen throughout, and participants were instructed to fixate the red button.
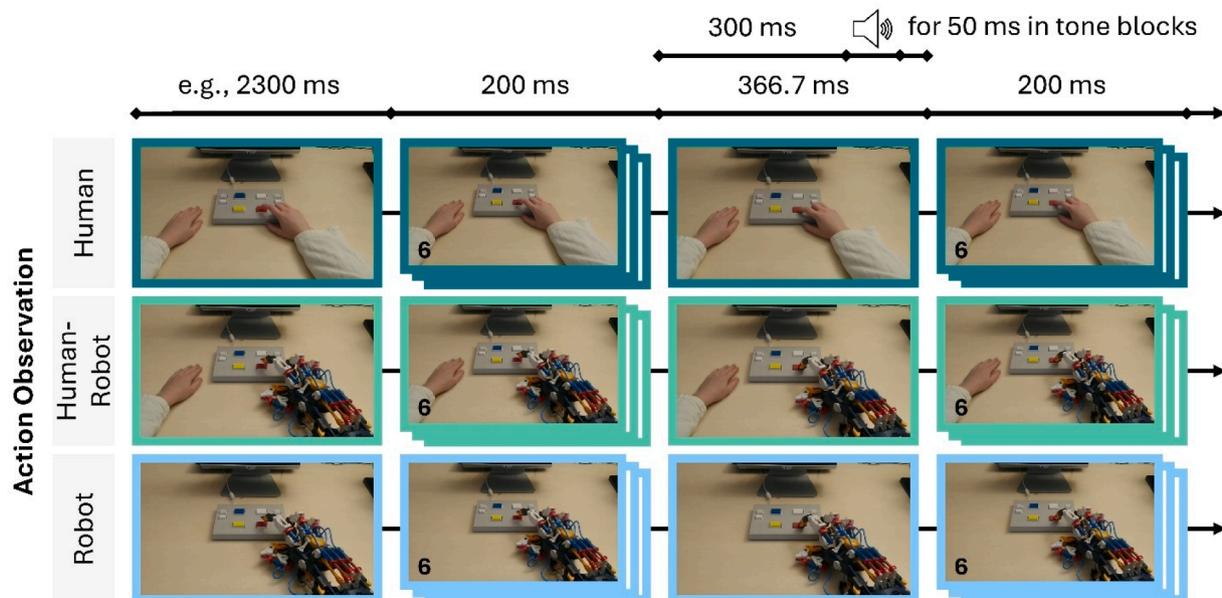
There were three action-observation conditions (i.e., human, human-robot, and robot). In all three conditions, the button press (of the red button on the response box) was viewed from a first-person perspective and shown via a sequence of pictures (see Fig. 2). In the human action-observation condition, participants observed a right human hand pressing the button. Additionally, a left human hand was visible on the side to further highlight that the agent was human. In the human-robot action-observation condition, participants observed a right robotic hand pressing the button, with a left human hand visible on the side, and were instructed that a person was controlling the hand (i.e., human agent with robotic depiction). In the robot-action observation condition, participants viewed a right robotic hand pressing the button without a depiction of a left hand and were instructed that the computer controlled it (i.e., computer as agent with robotic depiction). In the experimental blocks of all action-observation conditions, the tone was elicited 300 ms after the picture showing the button completely pressed (see Fig. 2 for the timings) and instructions were to fixate the red button, observe the button press, and listen to the tones. As mentioned above, there were control blocks, in which observed button presses did not elicit tones. The inter-trial-intervals for all action-observation conditions (experimental and control blocks) were determined by the function described above. However, due to a latency error of the stimulus-presentation monitor, each picture was presented for one more frame than intended and the intervals, which were calculated based on the a priori duration assumptions, were consistently longer for all blocks of the action-observation conditions (M = 2881–2895 ms, SD [across participant means] = 35–43 ms).

1.2.2. Additional conditions

In the experimental block of the self-generation condition, participants were instructed to press a particular button (the red button on the response box) in the learned rhythm of 2400 ms (see Experimental Procedure) and the button press elicited a tone 300 ms after onset. In the control block, participants were also instructed to press the button in the learned rhythm, but no tone was elicited. Similar to the external

Action Observation
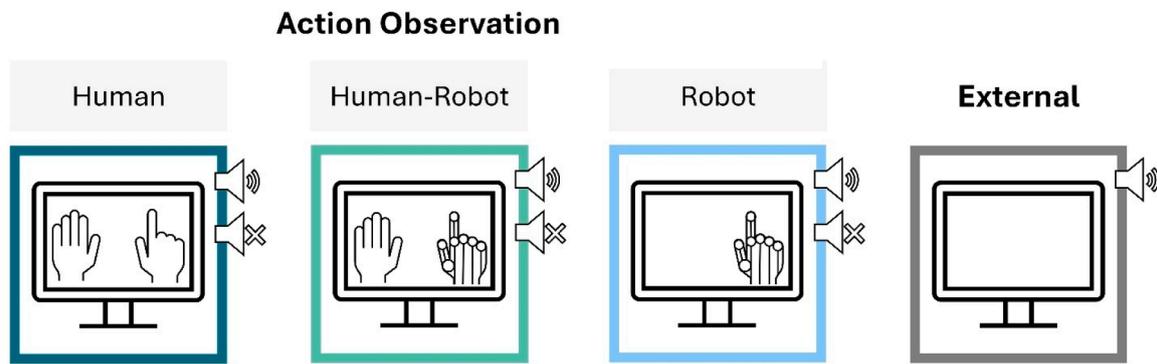
Fig. 1. *Experimental Design. Note.* Each condition is depicted and its related blocks are indicated with the sound-signs. For example, the human action-observation condition consisted of one experimental block (in which the observed button press elicited a tone as indicated by the active sound-sign) and one control block (in which the observed button press elicited no tone as indicated by the muted sound-sign). In the contingent paradigm (Horváth, 2015), the block in which the self-performed button press elicits no tone serves to correct for button-press-related (and thus tone-unrelated) activity in the event-related potentials of the self-generated tones. We applied the same procedure for the action-observation conditions, and therefore, included a control block for each. The same approach was applied to the conditions with self-generated and visually cued tones (see Supplement - Statistical Analyses for All Conditions).

Fig. 2. *Trials in the Action-Observation Conditions. Note.* The timings in the human, human-robot, and robot action-observation conditions were identical. After a random interval presenting the first picture, the sequential presentation of six pictures (each presented for 33 ms, i.e., two frames) led to the picture of the completely pressed button. During the presentation of this picture the tone was played. Then, a second picture sequence showing the same six pictures in reverse order led back to the first picture for the subsequent trial.

condition, a picture of the response box was shown on the computer screen throughout, and participants were instructed to fixate the red button. In the cue condition, participants saw a white circle appear and disappear on the red button of the response box pictured onscreen that was pressed or observed to be pressed in other conditions (self-generation and action-observation). Timings were kept comparable to the action-observation conditions, in that the same procedure was applied but the six pictures in the videos and the picture shown while the tone was played were identical. In the experimental block, the tone was presented 500 ms (i.e., the sum of the duration of the button-press motion and the action-outcome delay in the action-observation conditions) after the onset of the white circle. In the control block, the white circle was not followed by a tone. The inter-trial-intervals were determined by the function described above and, as for the action-observation conditions, were consistently longer than in the external condition ($M = 2881$ and 2897 ms, SD [across participant means] $= 43$ and 48 ms).

1.3. Questionnaires

We included four questionnaires to assess inter-individual differences in traits between participants, which could potentially modulate attenuation for (self-performed action or) action observation. The Cardiff anomalous perceptions scale (CAPS; Bell et al., 2006) assessed anomalous perception. The CAPS has 32 items, based on which a total score (i.e., number of items the participants claimed to have experienced) and three rating scores were calculated. These ratings were done on 1-to-5 scales for distress, intrusiveness, and frequency; and the rating scores were calculated as the sum of these (items not endorsed by the participants had a value of 0). For example, one item was: "Do you ever notice that sounds are much louder than they normally would be?" If the participant endorsed the item, they rated how distressing this anomalous perceptual experience was, how distracting it was, and how often it occurred. Furthermore, a questionnaire measure of trait empathy (22-item short form of the EQ; Wakabayashi et al., 2006) was

considered. This yielded a single score, the EQ.

Given the use of robotic depictions, we additionally included a measure of anthropomorphism (AQ; Neave et al., 2015), and a questionnaire that scores general attitudes towards robots (GAToRS; Koverola et al., 2022). For the AQ, a sum score for the two sub-scales regarding childhood-related items (10 items, e.g., "When I was a child, I made sure that when I put my toys away the ones who were friends were placed side by side") and items regarding current (i.e., adult) beliefs and behaviours (10 items; e.g., "I sometimes wonder if my computer deliberately runs more slowly after I have shouted at it"), and a total score were calculated (i.e., sum of the sub-scale scores). The GAToRS included four attitude factors and resulted in four scores with five items each: personal level positive (i.e., comfort and enjoyment around robots), personal level negative (i.e., unease and anxiety around robots), societal level positive (i.e., reasonable hopes about robots in general), and societal level negative (i.e., reasonable worries about robots in general).

To evaluate the stimuli of the action-observation conditions (see Supplement: Creation and Evaluation of Visual Stimuli) participants were asked to rate them on four items of the anthropomorphism scale of the Godspeed questionnaire series (Bartneck et al., 2008). Three items pertained to the overall impression (fake vs. natural, machine- vs. humanlike, and artificial vs. lifelike). One item related to the observed movement (moving rigidly vs. moving elegantly). Each item was rated on a 5-point-Likert scale.

1.4. Experimental procedure

The entire acquisition took about 2.5 h. Participants first filled out a demographic questionnaire and the questionnaires assessing the traits described above (see Questionnaires). Then, participants were prepared for EEG recording (see Data Recording) and were seated in the recording chamber in front of a 22-inch LCD computer screen (resolution: 1680*1050, refresh rate: 60 Hz) and a Cedrus RB-844 response box (Cedrus Corporation, San Pedro, CA, USA). Sennheiser HD 201 headphones (Sennheiser electronic SE & Co. KG, Wedemark, Germany) were placed on top of the EEG cap before the experiment was started. The experiment was run with the Presentation software (Version 20.3, Build 02.25.19; Neurobehavioral systems, Inc., Berkeley, CA, USA).

Before running the experimental conditions, consisting of experimental and control blocks (see Experimental Design and Conditions), participants underwent training that was divided into two blocks. The first block of the training served to introduce participants to the rhythm that they later had to reproduce during the self-generation experimental block and the respective control block. Eighty tones were played every 2400 ms and participants were instructed to press the button simultaneously. The tone (680 Hz, 50 ms duration, increase of amplitude in the first and decrease in the last 5 ms) was identical throughout the experiment. In the second training block, participants were instructed to press the button in the learned rhythm to elicit a tone, and they received feedback if they were too fast (< 1800 ms) or too slow (> 3000 ms). The tone occurred 300 ms after button press onset. In this block, as in all subsequent blocks, three tones were presented in the 2400 ms intervals at the beginning to remind participants of the learned rhythm and each block contained 80 trials (i.e., 80 button presses in this block).

The following blocks belonged to the experimental conditions (see Experimental Design and Conditions) and could be categorised into experimental and control blocks. The order of experimental blocks (one per condition, six in total) was randomised, as was the order of control blocks (one per condition, except for the external condition, five in total). However, participants were presented with either all experimental blocks first or all control blocks first. After each tone block, as an explicit measure of the sense of agency, participants responded to two questions. In an agency judgement, they were asked to judge who the agent of the tone was: themselves, another person, or the computer. This was included as an instruction check. Then, they rated how strongly they

ascribed agency to the chosen agent on a 6-point-Likert scale (i.e., agency-confidence rating). At the end of the experiment, three trials of each of the three action-observation conditions were presented without tones and participants were asked to rate the observed hand on the four selected items of the Godspeed questionnaire series (Bartneck et al., 2008; see Questionnaires).

1.5. EEG acquisition and data preparation

1.5.1. Data recording

EEG data were recorded with BrainVision Recorder (Version 1.21.0402) and a BrainAmp MR Plus amplifier (Brain Products GmbH, Gilching, Germany). Twenty-eight passive Ag/AgCl electrodes and an electrode at AFz serving as ground were placed on an Easycap electrode cap (see Fig. 3B for electrode sites; Brain Products GmbH, Gilching, Germany). Reference electrodes were placed on the mastoids. To record vertical and horizontal eye movements, further electrodes were placed at the cap positions F9, F10, and FP2, and under the right eye. For the recording, the sampling rate was set to 1000 Hz and notch and other software filters were disabled. Impedances were kept below 10 kΩ and direct-current corrections were applied online.

1.5.2. Pre-processing

With BrainVision Analyzer (BVA; Version 2.2.0.7383, Brain Products GmbH, Gilching, Germany) the following pre-processing steps were done. We applied a direct current detrend and Butterworth zero phase filters with a low cut-off of 0.1 Hz, a high cut-off of 30 Hz, and a notch filter of 50 Hz. The BVA's ocular correction independent component analysis was applied (steps = 512, Infomax restricted biased) and two to three components of blinking and eye movement artifacts were manually selected and removed. Because the EEG data of some participants clearly indicated that they had closed their eyes, the data was specifically screened to identify and mark intervals showing alpha activity on most electrodes and longer blinks or blink-like activity with the raw data inspection function in BVA. A second rater checked the validity of the markings. Segmentation was done in two steps to apply trial exclusion criteria on a wider pre-tone interval. First, segments beginning 400 ms before and ending 400 ms after tone markers were extracted. Note that tone markers were also sent in the control blocks, but the tones were muted. In this step, all segments with intervals marked in the raw data inspection were excluded as well as those, in which participants pressed the button, although, according to the instructions, they were not required to do so (i.e., in all blocks except the experimental block of the self-generation condition and its control block). Furthermore, only segments with preceding inter-event intervals between 1800 and 10000 ms were considered and, for the self-generation condition, segments of double presses (i.e., when a second button press followed the button press after less than 800 ms) were also excluded. In the second segmentation step, the segments were shortened, yielding segments beginning 100 ms before the tone markers with a total length of 500 ms. The first 100 ms were used for the subsequent baseline correction. For artifact rejection, we applied the automatic procedure in BVA: maximal allowed voltage step: 50 μV/ms, maximal allowed difference of values in 100-ms intervals: 100 μV, allowed amplitudes: −100–100 μV, lowest allowed activity in 100 ms: 0.5 μV (see Table 1 for numbers of trials retained in each block). Averages across trials were calculated for control blocks for use in the correction procedure (see next section).

1.5.3. N1 and P2 amplitude extraction

For the remaining data preparation, we used R (Version 4.4.2, R Core Team, 2024). For the self-generation, action-observation, and cue conditions, the ERPs were corrected for tone-unrelated activity (cf. motor correction in contingent paradigm; Horváth, 2015). For this purpose, average ERPs of the control blocks were subtracted from the single-trial ERPs of the respective experimental blocks (for a visualisation, see Supplement: Visualisation of ERP Correction Procedure). Based on the
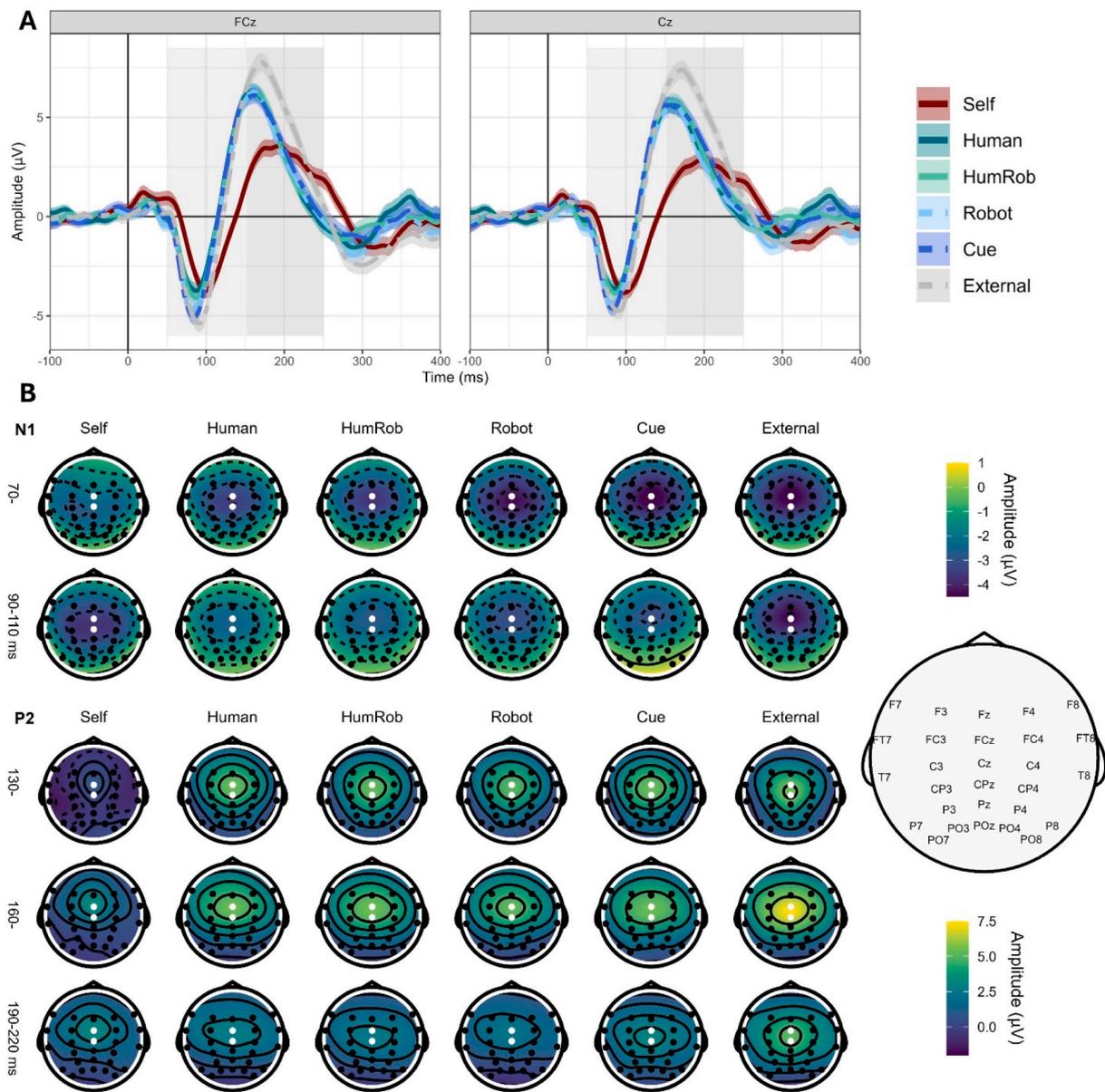
Fig. 3. *Condition-Specific Grand-Average ERPs and Topographies. Note.* A: Grand-average ERPs for each condition and confidence intervals are plotted. This refers to the corrected ERPs for self-generation, action-observation (human, human-robot, and robot), and cue conditions. Grey areas mark the time intervals of the peak detection. B: Topographies for the separate conditions are depicted. Time intervals were chosen based on the minimal and maximal peak latency and the amplitude extraction interval (20 ms around the peak for the N1, 40 ms for the P2). For the N1 (min: 82, max: 99), this covers the interval between 70 and 110 ms in 20-ms bins, and for the P2 (min: 152, max: 195), the interval between 130 and 220 ms in 30-ms bins. Electrodes FCz and Cz are highlighted in white. The countour lines in the topographies are dashed for negative amplitude values and solid for positive ones. The plots were generated in R using the packages packages *ggplot2* (Wickham, 2016), *eegUtils* (Craddock, 2024) and *ggpubr* (Kassambara, 2023). Note that latency differences of N1 and P2 are visible between self, visual (action-observation [human, human-robot, robot] and cue), and external conditions. HumRob = Human-robot.

topographies of the grand averages for the corrected ERPs of each condition, FCz and Cz were identified as the electrodes with the most pronounced N1 and P2 peaks (see Fig. 3B; cf. Ghio et al., 2018; Han et al., 2021; Harrison et al., 2021; Klaffehn et al., 2019) and chosen for further analysis. Because of latency differences between the conditions, N1 and P2 peaks were determined based on condition-specific grand averages of the corrected ERPs across participants (see Fig. 3A). The N1 peak was determined as the local minimum in the interval between 50 and 150 ms for each condition (condition: FCz/Cz; self-generation: 99/98 ms, human: 87/86 ms, human-robot: 87/86 ms, robot: 83/82 ms, cue: 84/83 ms, external: 91/90 ms). Mean amplitudes were extracted from the 20-ms interval in each single trial, centred around the respective condition-specific peak latency (cf. Harrison et al., 2021; Jack

et al., 2021; Neszmélyi et al., 2022; van Laarhoven et al., 2021). The P2 peak was determined as the local maximum in the interval between 150 and 250 ms for each condition (condition: FCz/Cz; self-generation: 192/195 ms, human: 158/155 ms, human-robot: 160/159 ms, robot: 162/161 ms, cue: 162/152 ms, external: 170/171 ms). As the P2 waveform was generally wider than the N1 (see Fig. 3), mean amplitudes were extracted from the 40-ms interval in each single trial centred around the respective condition-specific peak latency (cf. Klaffehn et al., 2019; Pinheiro et al., 2019; van Laarhoven et al., 2021).

1.6. Statistical analysis

We used R for all statistical analyses, including the calculation of

Table 1
Numbers of trials after exclusions

Condition	Block	*M*	*SD*	Minimum	Maximum
Self-generation	Experimental	75.60	4.79	63	79
	Control	76.20	3.76	73	79
Action-Observation	Experimental	76.53	4.66	60	79
Human	Control	77.45	1.72	73	79
Action-Observation	Experimental	76.95	3.52	66	79
Human-Robot	Control	77.62	2.33	67	79
Action-Observation	Experimental	77.08	3.93	57	79
Robot	Control	77.10	2.72	69	79
Cue	Experimental	75.72	5.07	62	79
	Control	77.38	2.48	69	79
External		72.90	7.01	37	79

Note. All participants retained at least 70% of trials (56 trials) in all blocks with one exception: 37 trials in the external condition due to a belated start of recording.

mixed-effects models. In the analyses reported here only the three action-observation conditions and the external condition were considered. For the analyses including all conditions (i.e., also self-generation and cue conditions) see the Supplement (Statistical Analyses for All Conditions). The effect of agent-condition (human action-observation, human-robot action-observation, robot action-observation, external with external as reference) was analysed for agency-confidence ratings, and N1 and P2 amplitudes. Additionally, potential modulations of the N1 and P2 attenuation by various trait scores and by the agency-confidence ratings were tested.

Because of the single-item ratings of agency-confidence, we used the *ordinal* package (Christensen, 2023) to calculate a cumulative link mixed model on the ratings. For the N1 and P2 amplitudes, we used the *lme4* (Bates et al., 2015) and *lmerTest* packages (Kuznetsova et al., 2017) to calculate linear mixed models. These linear models were calculated with the optimiser *bobyqa* and using the restricted maximum likelihood for model reporting and the maximum likelihood for model comparisons (Meteyard & Davies, 2020). For decomposition of fixed-effects contributions, the *anova* function was used for the mixed linear models (with a function to determine effect sizes by the package *effectsize*, Ben-Shachar et al., 2020). Estimated means and Bonferroni-corrected pairwise comparisons for significant effects were calculated with the package *emmeans* (Lenth, 2022). The package *performance* (Lüdecke et al., 2021) was used for model comparisons, which included likelihood ratio tests and Bayes Factors (BF). The package calculates BFs using the BIC approximation. We consistently report BF_{10} and thus values greater than 1 indicate evidence in favour of the extended model. Model comparisons were part of our model building procedure and of the analyses of potential modulations of the N1 and P2 attenuation by trait scores and agency-confidence ratings. Adopting a conservative approach, we not only considered whether the more complex model improved model fit according to likelihood ratio tests, but also whether this improvement justified the complexity, as the BFs favour parsimonious models.

1.6.1. Agency judgements and confidence ratings

When exploring the data, we noted that, despite clear instructions, the agency judgements (i.e., identifying the agent as oneself, another person, or the computer) were not in all cases as intended (i.e., in human and human-robot action-observation conditions as another person, and in robot action-observation and external conditions as the computer). The number of participants who judged the agent according to the instructions in all conditions was 17. On average, participants made 0.85 deviant judgements (*SD* = 0.83, range: 0–2). To determine whether these discrepancies occurred consistently across conditions, we first calculated a generalised linear mixed-effects model with only the intercept and random intercept by participant: Intended agency judgement (0 for not intended, 1 for intended) ~ 1 + (1 | participant). Adding agent-condition as fixed-effect did not improve the model, $\chi^2(3) = 4.46$, $p = .216$ ($BF_{10} < 0.01$) and was therefore not further evaluated.

Descriptively, the highest proportions of intended agency judgements were in the external condition (estimated $M = 0.88$), while in the robot action-observation (estimated $M = 0.83$) and especially the human (estimated $M = 0.75$) and human-robot conditions (estimated $M = 0.70$), participants made more agency judgements that differed from the instructions. Then, a cumulative link mixed model for the judgement responses (i.e., self, other, and computer) was defined with only the intercept and random intercept by participant: Judgement ~ 1 + (1 | participant); and a model including also agent-condition as fixed effect. The model fit was improved by agent-condition, $\chi^2(3) = 62.36$, $p < .001$ ($BF_{10} > 1000$), indicating differences across conditions. Pairwise comparisons between conditions showed the expected significant differences resulting in one cluster including external and robot action-observation conditions, and a second cluster including human-robot and human action-observation conditions. Thus, although the action-observation conditions (human, human-robot, and robot) descriptively showed more deviations from the condition instructions in agency judgements than the external condition, the overall pattern of judgements was as intended.

To analyse the 6-point-Likert scale agency-confidence ratings, a cumulative link mixed model was defined which, in a first step, comprised only the intercept and random intercept by participant: Rating ~ 1 + (1 | participant). The fixed effect agent-condition was added, Rating ~ agent-condition + (1 | participant), and the models were compared. The addition of agent-condition as a fixed effect improved the model fit only according to the likelihood ratio test, $\chi^2(3) = 10.64$, $p = .014$, not the BF ($BF_{10} = 0.10$); the addition of the judgement responses (i.e., oneself, another person, and the computer) as additional predictor of the ratings, $\chi^2(2) = 2.12$, $p = .347$ ($BF_{10} = 0.02$), or the addition of judgement accuracy (i.e., intended vs. not intended), $\chi^2(1) < 0.01$, $p = .971$ ($BF_{10} = 0.08$), did not. Therefore, the model with only agent-condition as fixed effect was further analysed with pairwise comparisons.

1.6.2. Linear mixed models for N1 and P2 amplitudes

To determine the random effect grouping factors, models were calculated with the maximum likelihood method and first defined with only the intercept as fixed effect and a random intercept by participant. In a next step, electrode (FCz, Cz) was considered as another random-effect grouping factor to account for site-specific variability while keeping the model parsimonious, as the effect of electrode on amplitudes was not of primary interest. For the N1, the addition of a random intercept by electrode to the model did not improve model fit, $\chi^2(1) = 1.46$, $p = .227$ ($BF_{10} = 0.01$). Adding agent-condition as fixed effect, $\chi^2(3) = 57.66$, $p < .001$ ($BF_{10} > 1000$), and adding a random by-participant slope for agent-condition, $\chi^2(9) = 226.72$, $p < .001$ ($BF_{10} > 1000$), greatly improved model fit. The final model, N1 ~ agent-condition + (agent-condition | participant), was recalculated with the restricted maximum likelihood method and further analysed with an analysis of variance and pairwise comparisons.

For the P2, the addition of a random intercept by electrode to the starting model did not improve model fit convincingly, $\chi^2(1) = 8.03$, $p = .005$, as the BF_{10} was 0.36, whereas the addition of agent-condition as fixed effect, $\chi^2(3) = 96.68$, $p < .001$ ($BF_{10} > 1000$), and the addition of a random by-participant slope for agent-condition, $\chi^2(9) = 394.09$, $p < .001$ ($BF_{10} > 1000$), greatly improved model fit. The final model, P2 ~ agent-condition + (agent-condition | participant), was recalculated with the restricted maximum likelihood method and further analysed with an analysis of variance and pairwise comparisons.

1.6.3. N1 and P2 models including trait scores

To investigate modulations of the N1 and P2 amplitude in the different agent-conditions by anomalous perception, empathy, anthropomorphism, and attitudes towards robots, model comparisons were planned. The N1 and P2 models resulting from the model building procedure described above (i.e., base model) were extended by one of the trait scores at a time (main and interaction effect). The base and

extended models were then compared. For the N1, the trait models took the form: N1 ~ agent-condition*trait score + (agent-condition | participant); likewise, for the P2: P2 ~ agent-condition*trait score + (agent-condition | participant). A total of 12 such extended models were calculated for each component. One model was calculated for empathy with the total score. For anomalous perception, the total score and three sub-scores (distress, intrusiveness, and frequency) were used in four separate models. Likewise, the total score and two sub-scores (childhood and current) were used for three models for anthropomorphism, and for the attitude towards robots, the four sub-scores (personal level positive, personal level negative, societal level positive, and societal level negative) were used in four separate models. For each trait score, the values were standardized by subtracting the mean and dividing by the standard deviation before adding the trait score to the basic model and comparing the models. To correct for multiple comparisons, the significance level for these model comparisons was adjusted to .004 using the Bonferroni correction.

1.6.4. N1 and P2 models including agency ratings

To investigate modulations of the N1 and the P2 by agency-confidence ratings, further model comparisons were planned. Again, the N1 and P2 models from the model building procedure (see above) were extended and compared. However, due to the unexpected variance of agency judgements, not only the agency-confidence ratings and the interaction with agent-condition were added as fixed effects. A subsequent model included also judgement accuracy and all interactions. The models were compared sequentially. For the N1, the extended models were: N1 ~ agent-condition*agency-confidence rating + (agent-condition | participant) and N1 ~ agent-condition*agency-confidence rating*judgement accuracy + (agent-condition | participant). Likewise, for the P2, the extended models were: P2 ~ agent-condition*agency-confidence rating + (agent-condition | participant) and P2 ~ agent-condition*agency-confidence rating*judgement accuracy + (agent-condition | participant).

2. Results

2.1. Agency-confidence ratings

Agency-confidence ratings are reported separately for each agent-condition and agency judgements in Fig. 4. Agency-confidence ratings were descriptively very high for the external condition (Mdn = 6). Ratings were descriptively lower for the action-observation conditions: human (Mdn = 5; estimate in relation to external: −0.47, SE = 0.46), human-robot (Mdn = 4; estimate in relation to external: −1.42, SE = 0.47), and robot (Mdn = 5; estimate in relation to external: −0.88, SE = 0.46). Ratings of the human-robot action-observation condition were significantly lower than in the external condition (p = .015). No other comparison reached significance (all ps > .17).

2.2. N1 and P2 models

The agent-condition ERPs are depicted in Fig. 5A. For the N1, the effect of agent-condition was significant, $F(3, 38.87) = 9.11$, $p < .001$, $\eta^2_p = .41$. The fixed-effect estimates are reported in Appendix A and the estimated means are depicted in Fig. 5B. The Bonferroni-corrected pairwise comparisons to the external condition reached significance only for human ($p = .002$) and human-robot action-observation ($p = .011$), indicating significant attenuation of the N1 in these conditions. All other comparisons were not significant (all $ps > .26$). To visualise the N1 attenuation effects, topographies for the attenuation contrasts are included in Appendix B. These show a frontal distribution of the effect.

For the P2, the effect of agent-condition was significant, $F(3, 38.77) = 7.99$, $p < .001$, $\eta^2_p = .38$. The fixed-effect estimates are reported in Appendix A and the estimated means are depicted in Fig. 5C. Bonferroni-corrected pairwise comparisons showed significant attenuation to the external condition for all action-observation conditions (human: $p = .007$, human-robot: $p = .005$, and robot: $p = .006$). The action-
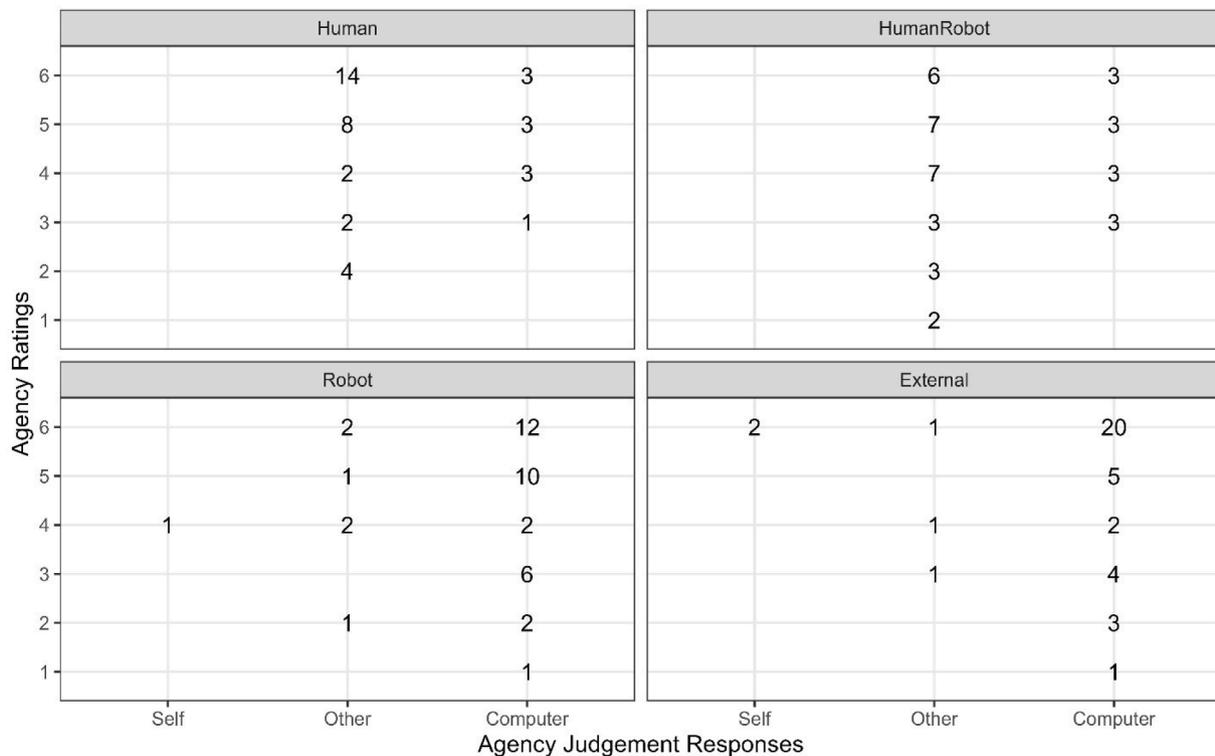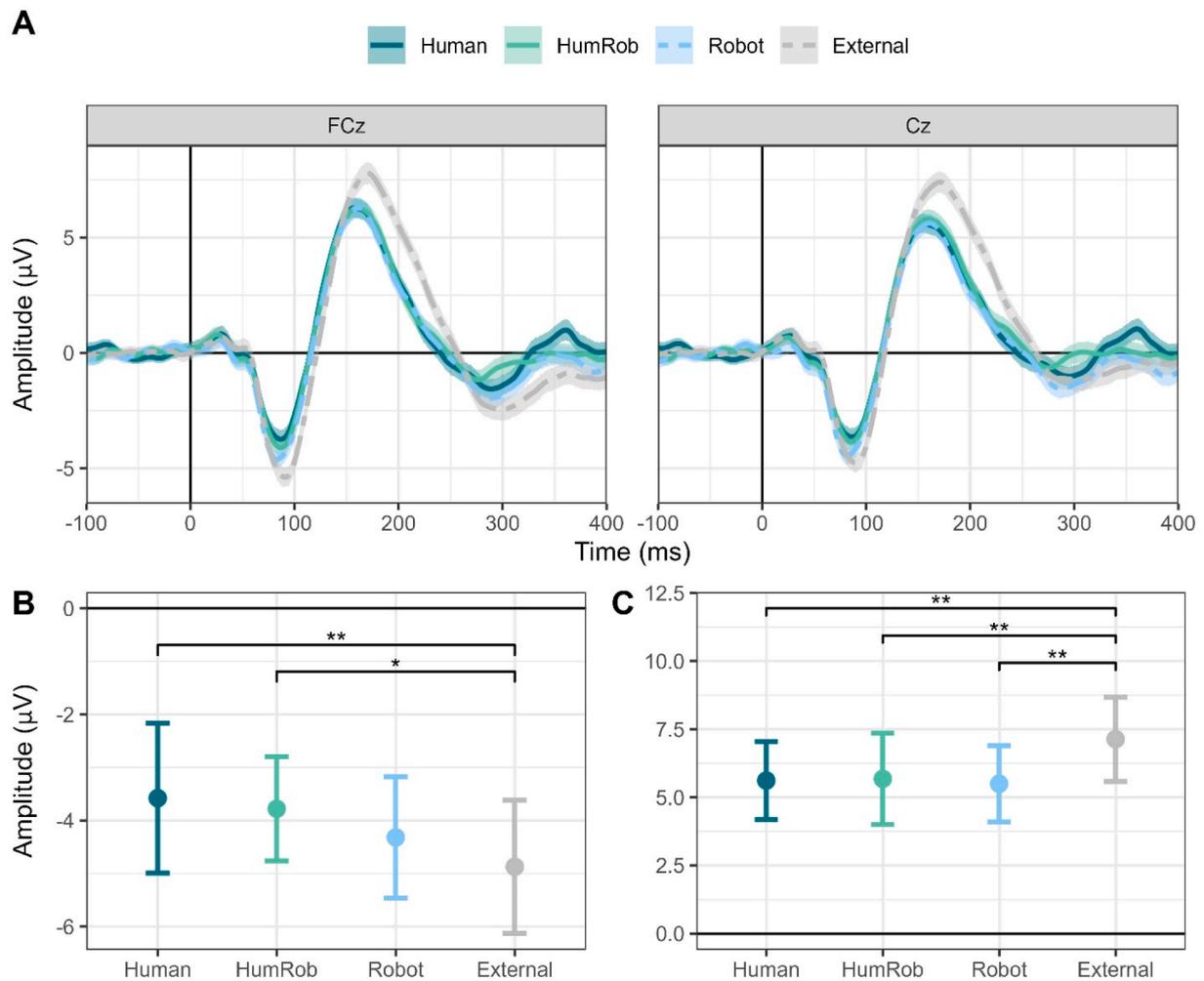

Fig. 4. *Agency-Confidence Ratings. Note.* The number of agency-confidence ratings for each level of the 6-point-Likert scale for each condition is listed separately for the respective agency judgement responses (oneself, another person, the computer).

Fig. 5. *N1 and P2 Results. Note.* The model formula for both components was: Amplitude ~ agent-condition + (agent-condition | participant). Agent-condition comprised the action-observation conditions (human, human-robot [HumRob], and robot) and the external condition. A: Condition-specific grand averages with confidence intervals. These are depicted for FCz and Cz. B: Estimated means with Bonferroni-adjusted confidence intervals for the N1. C: Estimated means with Bonferroni-adjusted confidence intervals for the P2. In B and C, significant Bonferroni-corrected pairwise comparisons are highlighted. The plots were generated in R using the packages *ggplot2* (Wickham, 2016), *ggpubr* (Kassambara, 2023), and *ggsignif* (Ahlmann-Eltze & Patil, 2021). * < .050, ** < .010, *** < .001.

observation conditions did not differ significantly from each other ($p > .99$). As for the N1, topographies for the P2 attenuation contrasts are included in Appendix B. Unlike the N1 attenuation, the P2 attenuation effects are centrally located.

2.3. Model comparisons: trait scores

Comparisons of models for the N1 and the P2 including trait scores are reported in Table 2. Likelihood ratio test with p-values below the adjusted significance level and BF_{10} greater than 1 indicate model improvement by the tested trait score. For the N1, the addition of the GAToRS societal-negative score improved model fit according to the likelihood ratio test but not according to the BF. As such, the model extended by this GAToRS score showed an improvement in fit, but this improvement was not sufficient to justify the added complexity, as indicated by the BF based on the BIC approximation. For none of the other trait scores did the model fit improve for the N1 or P2 according to the likelihood ratio test or the BF. In sum, no model extended by an obtained trait score convincingly improved model fit for N1 or P2 amplitudes.

2.4. Model comparisons: agency ratings

For the N1, the addition of the agency-confidence rating as predictor did not improve model fit, $\chi^2(4) = 2.23$, $p = .69$ ($BF_{10} < 0.01$), and the obtained model was also not improved by the further addition of agency judgement accuracy, $\chi^2(8) = 11.62$, $p = .17$ ($BF_{10} < 0.01$). For the P2, adding agency-confidence rating did not improve model fit, $\chi^2(4) = 4.52$, $p = .34$ ($BF_{10} < 0.01$). Further adding agency judgement accuracy likewise did not improve model fit, $\chi^2(8) = 6.06$, $p = .64$ ($BF_{10} < 0.01$). In sum, the models including predictors related to explicit agency did not convincingly improve model fit for N1 or P2 amplitudes.

3. Discussion

In the present study, we explored effects of agency attribution on neurophysiological SA in action observation. This entailed comparisons of N1 and P2 amplitudes in response to tones that were generated by an observed action performed either by a human hand, a robotic hand controlled by a human agent, or a robotic hand controlled by a computer to respective ERP amplitudes of unpredictable external tones. We expected to find stronger P2 attenuation when the tones could be attributed to a human agent. P2 amplitudes in the action-observation conditions were attenuated compared to the temporally unpredictable

Table 2
Model comparisons including trait scores

Component	Model Extension	$\chi^2(4)$	p	BF_{10}
N1	Anomalous perception total	4.05	.400	< 0.01
	Distress	4.82	.306	< 0.01
	Intrusiveness	3.51	.476	< 0.01
	Frequency	5.14	.274	< 0.01
	Empathy	9.01	.061	< 0.01
	Anthropomorphism total	2.52	.642	< 0.01
	Childhood	2.69	.610	< 0.01
	Current	2.34	.674	< 0.01
	GAToRS			
	Personal-positive	5.73	.220	< 0.01
	Personal-negative	3.89	.421	< 0.01
	Societal-positive	1.49	.829	< 0.01
	Societal-negative	23.07	< .001	< 0.01
P2	Anomalous perception total	3.88	.423	< 0.01
	Distress	4.21	.379	< 0.01
	Intrusiveness	2.73	.604	< 0.01
	Frequency	5.80	.215	< 0.01
	Empathy	9.75	.045	< 0.01
	Anthropomorphism total	1.47	.832	< 0.01
	Childhood	1.90	.753	< 0.01
	Current	2.50	.644	< 0.01
	GAToRS			
	Personal-positive	2.29	.683	< 0.01
	Personal-negative	0.30	.990	< 0.01
	Societal-positive	12.72	.013	< 0.01
	Societal-negative	3.46	.484	< 0.01

Note. For the N1 and P2, models including only the fixed effect of agent-condition were compared to the respective model extended by one of the 12 trait scores. Likelihood ratio tests (significant *p*-values indicating that the extended model is better; adjusted significance level = .004) and Bayes Factors (BF_{10}; values greater than 1 indicating that the extended model is better) are reported. GAToRS = General attitudes towards robots scale

external tones. However, the P2 amplitudes did not differ between the action-observation conditions, and attenuation was thus not more pronounced for the conditions with a human agent. We further expected N1 attenuation for all action observation conditions compared to temporally unpredictable external tones. Descriptively, human action observation showed smallest N1 amplitudes, and in human-robot action-observation, robot action-observation, and external conditions N1 amplitudes were gradually more negative. However, significant attenuation relative to temporally unpredictable tones was found only for observation of a human and human-controlled robotic action (i.e., action-observation conditions with human agent). In additional analyses, we tested for modulations of N1 and P2 amplitudes by trait scores of anomalous perception, empathy, anthropomorphism, and attitude towards robots as well as by agency-confidence ratings. No such additional predictor significantly improved the models for N1 and P2 amplitudes.

3.1. Primary analysis: P2 attenuation and agency attribution

Based on previous findings (Egan et al., 2023), we expected an effect of temporal predictability, which would apply to all action observation conditions, as well as an effect of human agency on the P2 amplitudes. Temporal predictability is one of the confounds of the typical comparison of self-generated and un-cued external tones, as the former ones are temporally predictable and the latter ones are not (Hughes et al., 2013). For the P2, the results of the present study support the relevance of this aspect, as the amplitudes for all action observation conditions were reduced relative to the unpredictable external tones. However, the action-observation conditions did not differ in P2 amplitudes depending on agency attribution.

To determine the smallest fixed-effect estimate that we would have been able to detect in our study with a power above 80%, we did a post hoc sensitivity analysis for the contrasts human action observation vs. external and human vs. robot action observation using the *simr* package

(Green & MacLeod, 2016). For the observed fixed-effect estimate as well as for various set estimates, 1000 simulations provided a mean power value. Whereas the observed fixed-effect estimate of the human-external contrast was 1.52, an estimate of 1.24 was sufficient to be detectable with 80% power. On the other hand, the observed fixed-effect estimate of the human-robot contrast was −0.12, but our study was underpowered to detect effects smaller than 1.18 μV and can therefore only rule out larger effects. Thus, the difference between human and robot action observation in P2 amplitudes could be smaller (i.e., < 1.18) than expected based on our previous study (Egan et al., 2023), requiring a larger sample size to be detected, or there was no effect of agency attribution. The lack of agency-related modulation suggests there was only an attenuating effect of temporal predictability and contrasts with previous findings with live action observation (Egan et al., 2023; Sato, 2008). Our additional analyses (see Supplement: Statistical Analyses for All Conditions) revealed that the P2 amplitudes of self-generated tones were significantly attenuated compared to all other conditions including human action observation, which confirms P2 modulation beyond temporal predictability. The lack of attenuation for action observation may thus possibly be related to the action-observation setting (Egan et al., 2023; Ghio et al., 2021; Ghio et al., 2018). Interestingly, studies with interactive contexts found P2 enhancement of temporally predictable partner-generated tones (relative to self- and computer-generated tones; Bolt & Loehr, 2021), particularly when jointly generating the tone sequence in alternation (Bolt & Loehr, 2023), suggesting that different processes affect P2 amplitudes at the same time.

In this study, agency-confidence ratings were descriptively lower in the action-observation conditions compared to the external condition. However, the inclusion of explicit agency measures did not convincingly improve the P2 model. Thus, while the results of analyses of the explicit measures suggesting weaker agency attribution might explain the lesser P2 attenuation in action-observation conditions, the measures did not sufficiently account for more variance. This is possibly due to the noise in the data introduced by the constraints of the design, that is, clear instructions were given regarding the agent, perception of agency was not further manipulated (e.g., by varying action-outcome delays, Timm et al., 2016) and participants gave only one agency judgement and confidence rating per condition. As such, some participants may have perceived the agency judgement as a trick question. Taking this into account, the results of the agency-confidence ratings should be interpreted with caution, in particular because different reasonings could have led to low ratings. To better discern underlying factors, separate ratings for all potential agents might be obtained in future studies. Moreover, diverging findings for the P2 and explicit agency judgements (e.g., Weller et al., 2017) suggest that the P2 attenuation does not directly reflect the more explicit judgements of agency, and so would not necessarily relate to explicit agency measures.

3.2. Secondary analyses: N1 attenuation and trait modulation

N1 attenuation has been previously related to temporal predictability, as cued tones showed reduced amplitudes compared to unpredictable external tones (e.g., Kaiser & Schütz-Bosbach, 2018) and did not differ from self-generated tones in N1 amplitudes (e.g., Harrison et al., 2021). The same pattern was found for tones generated by an observed action (Bolt & Loehr, 2023; Ghio et al., 2018). However, our results for the N1 did not follow this pattern. Across human action-observation, human-robot action-observation, and robot action-observation conditions N1 amplitudes had progressively lower values. The N1 amplitude was significantly reduced only for the first two conditions compared to the unpredictable external tones. Regarding the contrast of human action observation and external tones, the post hoc sensitivity analysis, as described in detail for the P2 above, showed that effects of at least −0.95 μV were detectable with 80% power. The estimate we observed was −1.29, indicating that our study was adequately powered to detect this

N1 attenuation. Yet, in line with studies indicating no (e.g., Klaffehn et al., 2019) or a partial (e.g., Schafer & Marcus, 1973) effect of temporal predictability on the N1, there was no significant attenuation in the robot action-observation condition. It should be kept in mind, however, that the action-observation conditions did not differ significantly from each other. Studies on the perception of robotic movement found that it can activate the mirror neuron system as well (Van Overwalle & Baetens, 2009), increasingly so with increased human-likeness (Matsuda et al., 2016) and familiarity (Press, 2011). The linear progression of N1 attenuation across robot, human-robot, and human action observation may therefore relate to an increased vicarious feeling of agency based on increased mirror neuron activation for more human, and therefore more familiar, action observation.

In contrast, in a previous study, N1 amplitudes of tones generated by observed human action were only descriptively reduced and those of cued tones were significantly attenuated compared to un-cued external tones (Egan et al., 2023). However, in Egan et al. (2023) and the present study (see Supplement: Statistical Analyses for All Conditions) there was no significant difference in N1 amplitudes between action-observation and cueing conditions. Taken together, N1 attenuation is affected, at least in part, by temporal predictability, although N1 attenuation compared to unpredictable external tones for tones that are predictable by another's action or a visual cue is not robust. As part of our additional analyses (see Supplement: Statistical Analyses for All Conditions, for a more detailed discussion), we noted a lack of N1 attenuation for the self-generation condition, which is unusual and may be due to the reduced temporal proximity implemented in this study (Horváth et al., 2012; but see Klaffehn et al., 2019).

As in our previous study (Egan et al., 2023), we aimed to examine the influence of inter-individual differences assessed by questionnaires on neurophysiological SA. Extending N1 and P2 models by trait scores, we again did not find any significant improvement of the models and thus no convincing indication of attenuation modulations by traits of participants (Egan et al., 2023). Measuring perceptual SA, Cao and Gross (2015) likewise found no correlation with empathy scores, but, in contrast to our study, did find a correlation of SA values to trait scores measuring delusional ideation. It is possible that the sample of the present study was too small to detect such modulations by traits in healthy participants, that the applied questionnaires were not suitable, or that other experimental manipulations are needed to investigate the potential modulations of SA by empathy, anomalous perception, and anthropomorphism.

3.3. Limitations of the video implementation

Our planned stimuli evaluation was based on four items of the anthropomorphism scale of the Godspeed questionnaire series (Bartneck et al., 2008). Firstly, the naturalness, human-likeness, and lifelikeness were rated for our action-observation stimuli, and the scores were found to be significantly lower for the robotic hand than for the human hand (see Supplement: Creation and Evaluation of Visual Stimuli). As the (N1 and) P2 amplitudes in these conditions did not differ significantly, these do not seem to be important aspects for attenuation in action-observation. Secondly, the smoothness of movement of our action-observation stimuli was rated and, although robotic-hand movement was rated to be significantly more rigid than the human-hand movement, the ratings for all stimuli were relatively low (i. e., rated as moving rigidly; see Supplement: Creation and Evaluation of Visual Stimuli). This was probably due to the latency error of the stimulus-presentation monitor and might have led to lower perceived similarity in motion (less anthropomorphism) and less mirror neuron activation for human and robotic stimuli (Epley et al., 2007).

As another consequence of the latency error the inter-tone intervals in the action-observation condition were longer than intended. Importantly, the N1 and P2 are modulated by inter-trial-intervals (SanMiguel et al., 2013), which in this study were around 400 ms longer in the action-observation conditions than in the external condition. It is possible that the amplitude increases by the higher inter-trial-intervals led to an underestimation of the attenuation effect, although we yet observed N1 attenuation for two and P2 attenuation for all of the action-observation conditions. Another aspect related to the timing is that while the intervals were randomly drawn, the video sequence itself featured no variation, which could have further reduced the impression of naturalness. As a result, agency judgements may be largely ascribed to participants' readiness to accept the information given about the agent in the instructions.

We implemented an action-effect delay of 300 ms to allow participants sufficient time to predict tone onset (cf. Egan et al., 2023). On the one hand, previous neurophysiological studies have made use of longer action-effect delays and reported significant N1 attenuation for self-generation (e.g., Klaffehn et al., 2019; Lange, 2011). On the other hand, the role of temporal proximity for attenuation has been demonstrated with the coincidence paradigm (e.g., Horváth et al., 2012). Coincidental tones were presented while participants performed button presses and they found an attenuating effect of temporal proximity on N1 and P2 amplitudes (Horváth et al., 2012). Furthermore, with an action-effect delay more training trials appear to be needed to reduce N1 amplitudes (Aliu et al., 2009; Elijah et al., 2018). To avoid potential complications by the reduction of temporal proximity, future action-observation implementations might include different types of actions that have longer durations than a button press and present the tone immediately upon completion of the action.

Lastly, the surprising agency judgements, the exclusions of participants because they pressed buttons when they were not instructed to do so, and the exclusions of trials because participants closed their eyes were all indications of a lack of attention, possibly due to the length of the experiment. While the order of blocks was randomised, effects of tiredness may especially affect blocks that did not require actions from the participants, such as the action-observation conditions.

3.4. Future perspectives

Considering the limitations of our video implementation, future studies might investigate agency-related effects on the P2 attenuation by using more naturalistic timings (in motion and action-effect onset) or more explicit implications that another person is being observed. Alternatively, action observation might be implemented as live observation, for which P2 attenuation was found to be as strong as for self-generation (Egan et al., 2023; Ghio et al., 2021), and live observation of a robot or mechanical device. A promising avenue might be virtual reality. For instance, one study implemented a robotic agent as a sphere in virtual reality (Feder et al., 2023). However, the N1 of self-generated tones was attenuated compared to the robot-generated ones and the P2 was not, which is likely due to the lack of temporal predictability in the robot condition and the use of various action-outcome delays (Feder et al., 2023).

A relevant aspect might be the attribution of intentions, as indicated by studies on an effect termed intentional or temporal binding (e.g., Roselli et al., 2022). This binding effect describes the shift of perceived timings of action and effect towards each other (for a review see Moore & Obhi, 2012). Although the binding effect has also been discussed as an implicit measure of the sense of agency, it was suggested to result from different mechanisms than SA (Hughes et al., 2013), potentially linked to attentional (Schwarz & Weller, 2023) and temporal grouping processes (Gutzeit et al., 2023). Similarly to SA, however, the binding effect was found for action observation (e.g., Poonian & Cunnington, 2013). Studies including robotic agents found that in physical settings, as opposed to virtual settings, human-likeness was a relevant factor for finding the binding effect as well as action-occurrence (i.e., the robot performing a physical action, rather than a mere command transmission highlighted with visual cues on the robot; Roselli et al., 2022; Roselli et al., 2021). Further, a significant correlation of the perceived timing

shift with intentionality attribution to the robot was found (Roselli et al., 2022; Roselli et al., 2021). Therefore, intentionality ratings might also be obtained in future SA studies, to examine whether attributing intentions to the person or robot whom the participants observe modulates P2 amplitudes as well.

4. Conclusion

In the present study, we explored the role of agency attribution to a human agent for neurophysiological SA during action observation. Our results suggest that for action observation, the attenuation of N1 amplitudes is a less robust finding than that of P2 amplitudes and might be influenced by temporal predictability but cannot be fully explained by it. For the P2, all action-observation conditions showed attenuated amplitudes compared to external tones irrespective of agency attribution. For both components no differences between conditions with human and computer agents were found. However, we discussed how the observation setting might affect attenuation in action observation, which could be addressed in future studies. The present study supports the notion of a combination of predictive mechanisms yielding neurophysiological SA (Dogge et al., 2019; Horváth, 2015; Hughes et al., 2013).

CRediT authorship contribution statement

Christian Bellebaum: Writing – review & editing, Supervision, Resources, Conceptualization. **Marta Ghio:** Writing – review & editing, Supervision. **Constanze Weber:** Writing – review & editing, Validation, Methodology. **Sophie Egan:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The author(s) did not use generative AI technologies for preparation of this work.
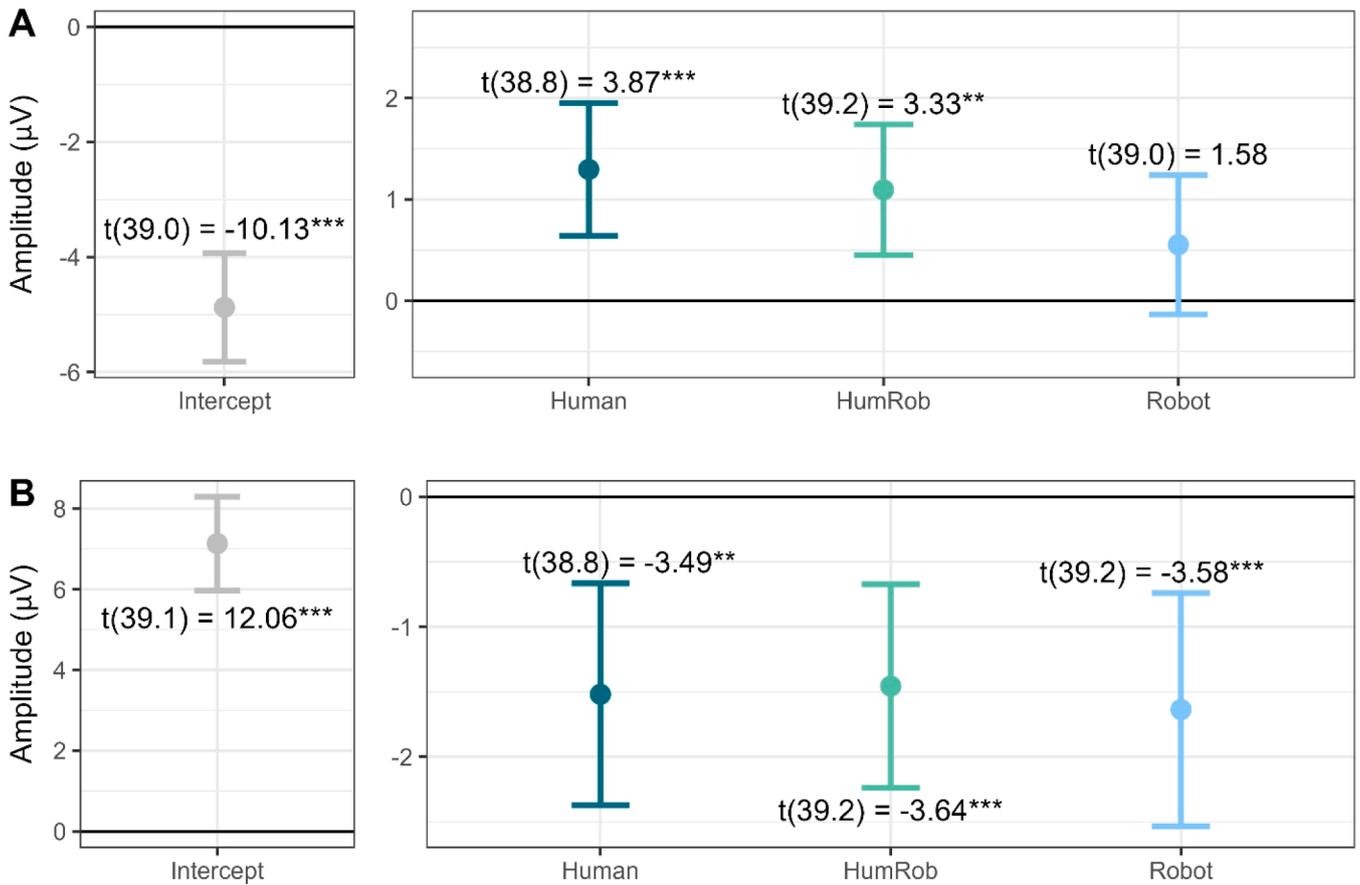
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. : N1 and P2 Model Estimates

N1 and P2 Model Estimates

Fixed-Effect Estimates (number of observations: 24276)

Note. Fixed-effect estimates of the models with confidence intervals are presented. The model formula for both components was: Amplitude ~ agent-condition + (agent-condition | participant). Agent-condition comprised the action-observation conditions (human, human-robot [HumRob], and robot) and the external condition. The external condition was the reference (i.e., it represents the intercept). Thus, the intercept panel shows the estimate of the external condition and that it differs from 0, while the adjacent panel demonstrates the differences of the other conditions to the external condition. A: N1 model. B: P2 model. The plots were generated in R using the packages *ggplot2* (Wickham, 2016) and *ggpubr* (Kassambara, 2023). * < .050, ** < .010, *** < .001

Appendix B. : Topographies of Attenuation Contrasts

Topographies of Attenuation Contrasts
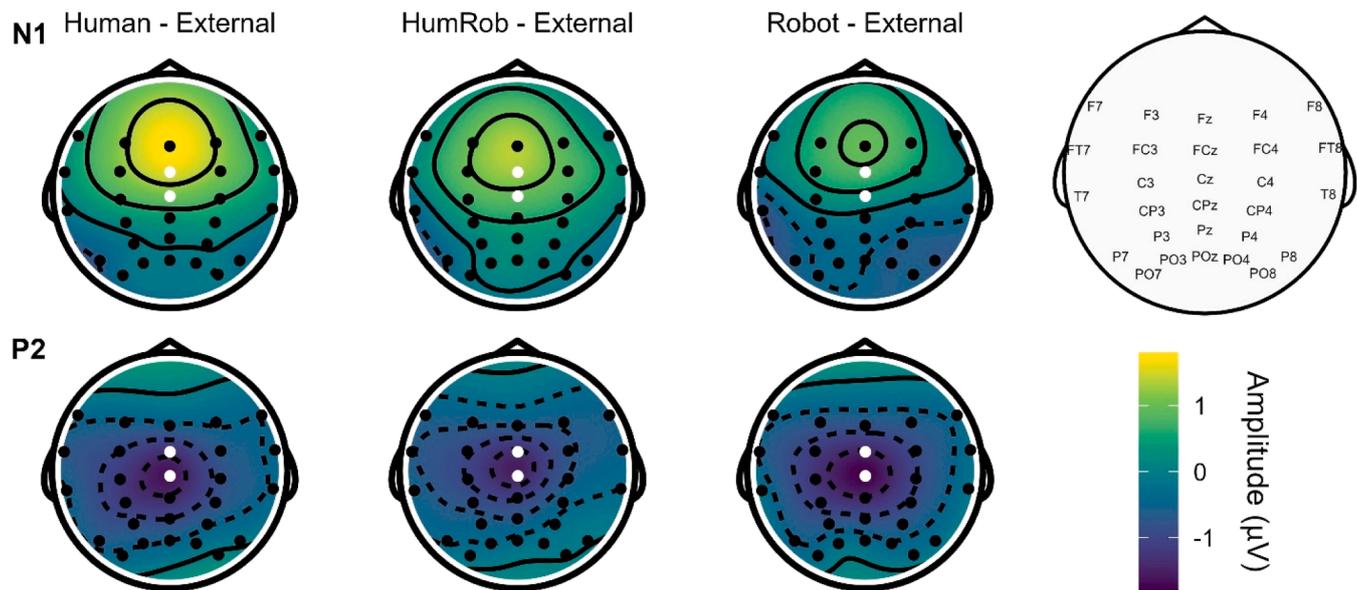
Note. Topographies of the attenuation contrasts are depicted for each action-observation condition. For this, the aligned 20-ms interval around the respective N1 peak was subtracted from the external condition. The same was done for the 40-ms interval around the respective P2 peak. The countour lines in the topographies are dashed for negative amplitude values and solid for positive ones. The plots were generated in R using the packages packages *eegUtils* (Craddock, 2024) and *ggpubr* (Kassambara, 2023)

Appendix C. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2026.109241.

Data availability

Data and code are available in an OSF repository.

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