OXFORD

ERP correlates of agency processing in joint action

Gethin Hughes, [ID]*, Peter Leslie Thomas Gooding

Department of Psychology, University of Essex, Colchester, CO4 3SQ, United Kingdom
*Corresponding author. Department of Psychology, University of Essex, Wivenhoe Park, Colchester, Essex CO4 3SQ, UK. E-mail: g.hughes@essex.ac.uk

Abstract

In the Ouija board phenomenon, the lack of agency experienced by the players leads them to attribute the movement of the planchette to spirits. The aim of this study was to investigate the neural and cognitive mechanisms involved in generating the sense of agency in such a joint action context. Two players (a participant and a confederate) jointly moved a Ouija board-style planchette containing a wireless mouse. This, in turn, moved a digital board on the screen. Participants reported a greater sense of agency in the condition where they had complete control of the planchette (the 'self' condition), and least agency when they passively held the planchette while it was moved by the confederate ('other' condition), with the two 'joint' action conditions in between. While the N1 peak did not differ between conditions, the early part of the N1 differentiated between the joint action conditions, and the solo action conditions. In contrast, the Tb and P2 components differed between the 'other' condition and the 'self' and 'joint' conditions. These findings are discussed with reference to motor-prediction and attentional mechanisms.

Keywords: sense of agency; sensory attenuation; joint action

Introduction

The sense of agency is defined as the feeling of being in control of your actions, and through them, events in the world (Haggard 2017). The sense of agency is often unambiguous. For instance, when you press a number on the control panel of an elevator, and the lift starts moving, you feel like your action caused the elevator to start to move. However, if you are in an elevator with two control panels, seeing another person reach for the other control panel at the same time would likely introduce uncertainty as to whether your action caused the lift to start moving. As outlined by Wegner (2002), the degree to which the outcome could only have been caused by you (the exclusivity principle) is a key determinant of the sense of agency. One context where this principle is seen to influence sense of agency is in the Ouija board phenomenon. Players hold a heart-shaped 'planchette' over a board marked with letters and numbers, while taking turns to ask questions. The players all hold the planchette, but they are told not to move it themselves. Instead, they should allow the spirits to spell out a response. By violating the exclusivity principle, each player surrenders their own sense of agency, and ultimately, they attribute the movements of the planchette to spirits.

Wegner and Wheatley (1999) highlighted how violating the exclusivity principle can be used to manipulate sense of agency in a Ouija board game. In their study, two participants (one of whom was a confederate) placed their hands over a board that

had been attached to a computer mouse. Although the confederate ultimately controlled where the board stopped, participants' agency was increased when they heard a prime word corresponding to the object that they stopped on, immediately before stopping. This shows that when the exclusivity principle is violated, an inserted thought consistent with the action outcome could increase the sense of agency.

The current study aims to extend this work by investigating the neural markers of sense of agency in a similar Ouija board context. As in Wegner and Wheatley (1999), a participant and a confederate jointly controlled the movements of a computer mouse to navigate around the screen. In our study, we compared a condition where participants had complete control over the movement of the mouse, a second condition where the participant simply held the mouse, which was controlled entirely by the experimenter, and then two intermediate conditions where participant and the confederate jointly moved the mouse. As such, the current study aimed to determine the neural mechanisms of agency attribution in joint action contexts.

Sensory attenuation is the phenomenon whereby self-generated action outcomes are attenuated (Hughes et al. 2013) compared to identical externally generated sensory stimuli. This is commonly assessed using the N1-suppression paradigm, whereby the auditory N1 ERP (event-related potentia component is significantly reduced for action-triggered tones, compared to externally triggered tones. Sensory attenuation is thought to come

about via an internal forward model, which predicts the sensory consequences of a particular motor command, sometimes referred to as an efference copy (Wolpert et al. 1995). When the observed sensory outcome matches the prediction, the sensory processing is attenuated (Hughes et al. 2013; Waszak, et al. 2012). Given that similar comparator mechanisms are linked to the generation of the sense of agency (Blakemore et al. 2000, 2002, Synofzik et al. 2008), sensory attenuation may be related to the sense of agency, although this link remains contested (Dewey and Knoblich 2014, Grunbaum and Christensen 2020).

Loehr (2013) investigated sensory attenuation of the N1 ERP component in a joint action context. In the solo condition, the tone would be triggered when the participant pressed the button, but in the joint condition, the tone was only triggered once both participants had pressed their button. They found that N1 attenuation was smaller for jointly generated tones compared to self-generated tones. This suggests that the magnitude of N1 attenuation might reflect differences in the 'degree' of agency that participants have over generating the outcome.

However, a number of studies have challenged the link between N1 attenuation and sense of agency. For instance, Weller et al. (2017) showed that while sense of agency was increased by filling the interval between an action and the outcome, this was not associated with an increase in N1 attenuation. Similarly, Han et al. (2021) found no N1 attenuation when agency (controlling whether a sound is played) is dissociated from action. In this study, participants watched a visual stimulus (a ticker-tape) count down towards the time when a sound would play. In active conditions, participants could trigger a sound by choosing not to press a button (Experiment 1) or b (Luck and Gaspelin, 2017) y pressing a button (Experiment 2) during the selection period. As such, participants could trigger a sound either through action (Experiment 2) or inaction (Experiment 1). These 'active' trials were compared to 'passive' trials where participants observed the same visual stimulus,(Delorme and Makeig, 2004) but were told at the start of a trial whether a sound would play, and hence had no control over the presentation (or not) of the action outcome. In both studies, they observed no N1 attenuation for active compared to passive trials, despite the fact that (Freedman et al. 2020) participants agency differed between these two conditions. They interpreted this finding to suggest that N1 attenuation is related to motor-based predictions, but not sense of agency.

The current study aims to further clarify the extent to which N1 attenuation might be modulated by the degree to which participants have control over their action. Unlike the study by Han et al. (2021), the outcomes in our study are directly triggered by participant actions, and as such motor-prediction mechanisms could drive both action-effect processing and experience of agency. Similar to Han et al. (2021), we also use a visual cue to warn participants about the timing of the upcoming sound in all conditions, meaning that unlike the previous study by Loehr et al (2013), where the sound in the joint condition was triggered by whoever pressed the button last, temporal predictability is matched across our different conditions. Given that temporal predictability is an important determinant of N1 attenuation (Hughes et al. 2013), this might drive the N1 attenuation effects that they observed. As such, the current study will provide new insight on whether N1 attenuation is modulated by agency in a joint action context.

In addition to N1 attenuation, recent studies have explored whether later auditory processing varies for self-generated action outcomes. Bolt and Loehr (2021) investigated N1 and P2

attenuation in a task, where two participants had to produce complementary actions in a sequence production task. They found no N1 attenuation, but they did observe attenuation of the P2 component for self-produced tones, relative to partner-produced tones. As such, they suggest that the P2 component might be important for differentiating self from other produced actions in a joint action context. Han et al. (2021) also observed an enhanced P2 (and suppressed Tb) when participants had control over whether or not the tone occurred through action or inaction (as described above). They interpreted the Tb modulation to reflect differences in sensory processing of the action effects that were independent of motor-prediction processes (since they were triggered by both action and inaction), while the P2 modulation might reflect agency processing. While Han et al. (2021) observed differences in P2 amplitude dependent on whether or not participants were in control of the presentation of the tone, they did not record participants' experience of agency. In the current study, we will record the degree to which participants experienced agency for the actions and outcomes in the different conditions, allowing us to further elucidate which ERP components are linked to the subjective experience of agency.

In the current study, we aimed to determine the neural signatures associated with differences in the experience of agency in a Ouija board game. Since N1 attenuation is thought to come about through motor-prediction mechanisms, any modulation of N1 dependent on agency condition would point to this as a mechanism of altered agency experience in this phenomenon. If no N1 modulation is observed, then this would provide evidence against the link between sensory attenuation and sense of agency. Alternatively, modulation of the Tb and/or P2 components would reflect differences in secondary auditory processing, which may be independent of motor-prediction mechanisms, but might relate to the experience of agency (Han et al. 2021).

Methods

The experimental protocol, sample size, and analysis pipeline for this study were pre-registered prior to data collection: https://aspredicted.org/4HB_4JK. Data and analysis scripts are available at https://osf.io/vp9hf/.

Participants

Per our preregistration, data were collected from 50 participants. All participants had normal or corrected-to-normal vision. All participants signed an informed consent prior to the experimental session and were free to withdraw at any point. The study was approved by the University of Essex ethics committee and was performed in accordance with the declaration of Helsinki. Participants were reimbursed £20 for participating in the experiment.

Three participants were excluded due to unusable electroencephalography (EEG) data files (two with missing trigger codes and one which failed to record). One additional participant was removed from the EEG data because noisy data lead to the removal of all but 34 trials across all conditions during artefact rejection (see details below). In our preregistration, we stated that all participants with fewer than 20 trials per condition would be excluded from the analysis. However, this would have led to the removal of 39 of 47 participants. This was an oversight on our part when creating the preregistration given that the experiment only consisted of 176 trials in total across the 8 conditions (22 trials per condition). This left a final sample of 46 participants (29 female),
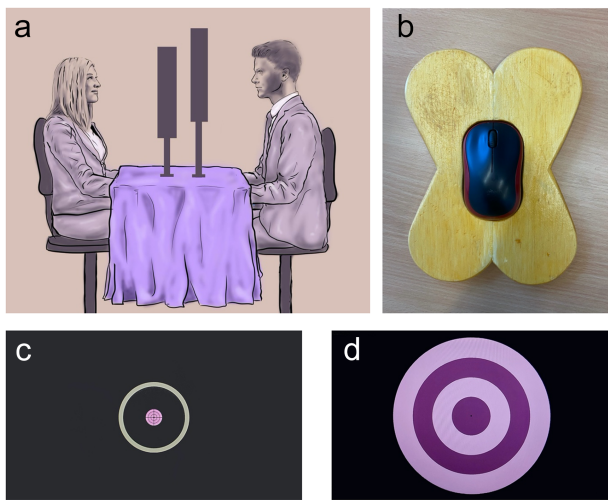
Figure 1. (a) Two participants (one confederate and one actual participant) sat facing each other with a table between them, each with their own monitor. (b) The participant and the confederate each held one side of the wooden planchette encasing a wireless computer mouse that is used to control the movement of the board around the screen. (c) Presented on each of the two monitors was a black opaque screen with a small (40 mm) circular view hole in the centre with a bull's eye. The shrinking grey circle indicates the passage of time towards the end of the trial (7 s in total). The trial ends when the grey circle meets the outer edge of the view hole, triggering either a sound or no sound (depending on the colour that the participant lands on). (d) The board, in its entirety, that is hidden behind the view hole. The board consisted of light and dark concentric purple circles. This board is moved by participants via their movement of the planchette, with the relevant section coming in to view through the central view hole.

with a mean age of 25.9 years and (range of 19–43 years). Of the 46 participants included in the EEG analysis, the mean number of trials retained across all conditions was 156 trials (SD = 17.9).

Materials and procedure

The experiment was conducted using Inquisit 6 Lab (millisecond.com), with visual stimuli presented on a 21-inch monitor, ∼60 cm from the participant. The auditory stimuli consisted of sine waves of 200 ms duration with 1000 Hz, presented via a loudspeaker positioned directly behind the participant. The task was a joint action task, in which two players (the participant and the researcher) moved a Ouija board style planchette encasing a computer mouse, which was used to navigate around the stimulus. The two players sat facing one another, each with a screen in front of each of them (obscuring their view of one another). These screens were placed on top of a stand placed over a desk. The planchette (containing a wireless mouse to register movement) was placed under the stand, where participants' view of it was obscured by a purple velvet cloth that was draped over the edge of the stand (see Fig. 1 for a graphical depiction of the experimental setup). The visual stimulus consisted of mostly a black opaque screen with a small (40 mm) circular view hole in the centre. The transparent view hole included a bull's eye to allow participants to precisely gauge the exact centre of the view hole (see Fig. 1c). Through this transparent view hole, participants could see a stimulus being moved corresponding to their movement of the planchette. The stimulus was made up of a series of concentric circles, alternating between light purple and dark purple (see Fig. 1d).

At the start of each trial, participants were asked to move the planchette in order to position the computer curser in the centre of the screen (a light purple circle). This started the actual trial. Following this they were asked to move the planchette in circular motions to explore the stimulus on the screen while keeping the planchette moving at all times. As they moved the planchette, these movements were reflected in the movement of the visual stimulus underneath the stationary view hole. This method was chosen to limit eye movements of participants during the task. Each trial lasted 7 s. The progression of time (7 s) was symbolized by a light grey ring that started out at the outer limit of the screen and slowly reduced in size towards the centre of the screen. The trial ended when this light grey ring collided with the view hole. This allowed participants to anticipate the end of the trial. Participants were informed that if the trial ended with the centre of the view hole over a light purple section of the board, they would hear a sound or that if the trial ends with the centre of the view hole over a dark purple section of the board, then they would not hear a sound. This meant that participants would be able to predict whether a tone would be played on each trial. Participants were asked to explore the stimulus as they saw fit but to aim to trigger a tone on approximately half of the trials while not on fixating on any kind of ordered response pattern. Participants triggered the sound on average on 85.9 trials (SD = 21.2), compared to 90.1 trials where no sound was triggered (SD = 21.2). This difference was not significant, t (45) = 0.66, P = .511. The sound (if triggered) was played 100 ms after the trial ended. We opted to associate the two different actions (colours) with either a tone or a no tone, in line with Han et al. (2021). While we did consider having each colour trigger a different tone, we decided against this because the role of identity prediction in N1 attenuation is unclear (see Harrison et al. 2023). Following an interval of 700 ms after the tone, participants were asked 'On a scale of 1–5, to what extent do you feel that you, rather than your partner, were responsible for whether or not the tone was played?'.

The experiment included four experimental conditions, across three different types of blocks, with the order of the different blocks counterbalance across participants. In 'Self Action' blocks, participants moved the board alone with the experimenter not touching the board at all. In 'Other Action' blocks, participants were required to passively hold the board, while the experimenter moved the board. As such, in these two conditions, the participant always held the moving planchette while observing the stimulus on the screen, but only in one condition did they have the capacity to control the outcome, providing a well-controlled contrast of agency. In 'Joint Action' blocks, participants were told that they would be moving the board together with the other participant. Unbeknownst to the participant these 'Joint Action' blocks actually contained two different types of trials: 'Joint' trials and 'Joint-self' trials.

In 'Joint' trials, the experimenter initially held on to the planchette (introducing very subtle perturbations to movement) but let go of the planchette 3 s before the end of the trial, so the participant ultimately had full control of the final movements of the board. As such, in this condition, participants' beliefs that they were acting collaboratively were reinforced by experiencing some subtle sensory indicators of shared control. In 'Joint-self' trials, the experimenter did not touch the planchette at all during the trial. As such, in this condition, we hoped to modulate participants agency experience merely through suggesting that the other player was also moving the planchette. Participants were not informed of these two different types of trials, which were signalled to the experimenter through headphones. The experiment

consisted of an initial practice block of 20 trials, followed by 6 blocks (2 of each block type) of experimental trials, with the order of the blocks counterbalanced across participants. 'Self Action' and 'Other Action' blocks included 22 trials each, while 'Joint Action' blocks contained 44 trials (22 'Joint' trials and 22 'Joint-self' trials). As such, the entire experiment consisted of 176 trials in total.

Electroencephalography recording and processing

EEG was recorded from 64 active scalp electrodes using a Neuroscan SynAmpsRT system connected to a PC running Curry 8 acquisition software. The ground electrode was at position AFz. The reference was placed on the nose as per Han et al. (2021), to allow calculation of the Tb component. Analysis was conducted using EEGlab (Delorme and Makeig, 2004) and custom-built Matlab scripts. Data were filtered with a high pass of 0.1 Hz and a low pass of 40 Hz to remove slow drift and line noise. Epochs were generated from −200 to 500 ms relative to the end of the sound (with the end of the action period at −100 ms). EEG data were baselined to the 100 ms immediately prior to the onset of the sound (−100 to 0 ms).

Noisy channels were identified by visual inspection and marked for later removal and interpolation (see below). On average, one bad channel was detected in each participant's data (range 0–5, with only one participant having more than three bad channels). Artifact rejection was conducted in an automatic manner (in EEGlab) by rejecting epochs with improbable data and abnormally distributed data, where the threshold in each case was set to 5 SD, or with absolute voltage outside the range of ±1000 μv. Ocular artifact correction was conducted in EEGlab in Matlab using independent component analysis (Delorme & Makeig, 2004). Following the removal of eye blinks and eye movements, a second round of artifact rejection removed any channels with absolute voltage outside the range of ±200 μv. Noisy channels were excluded from artifact rejection and were replaced by an interpolated weighted average from surrounding electrodes.

The analysis focused on three components of interest. The N1, Tb, and P2 components of the auditory-evoked potential. Component amplitude was calculated as the average voltage within a 30 ms time window, the centre of which was defined using the collapsed localizer approach (Luck and Gaspelin, 2017). For the N1 electrodes F1, F2, FCz, FC1, FC2, Cz, C1, and C2 were used, with the peak identified as the minimum voltage between 50 and 150 ms. For the Tb, the same time window was used to identify the time of the minimal amplitude at the average of electrodes T7 and T8. For the P2, the peak was identified as the maximum value across electrodes FCz, FC1, FC2, Cz, C1, C2, CPz, CP1, and CP2 between 110 and 210 ms. Average amplitudes were calculated for each component by taking the mean activity across the defined time windows for each electrode.

The agency ratings are reported using a 4 (condition: 'self', 'joint-self', 'other', and 'joint') × 2 (sound: sound and no sound) repeated measures Analysis of Variance (ANOVA). ERP analysis focused on the four components of interest (N1, Tb, P2, and P3) in the sound condition only. Repeated measures ANOVA was conducted with the factor condition ('self', 'joint-self', 'other', and 'joint') and electrode (dependent on the component being analysed). Where significant effects were observed, these were followed up with repeated measures t-tests.
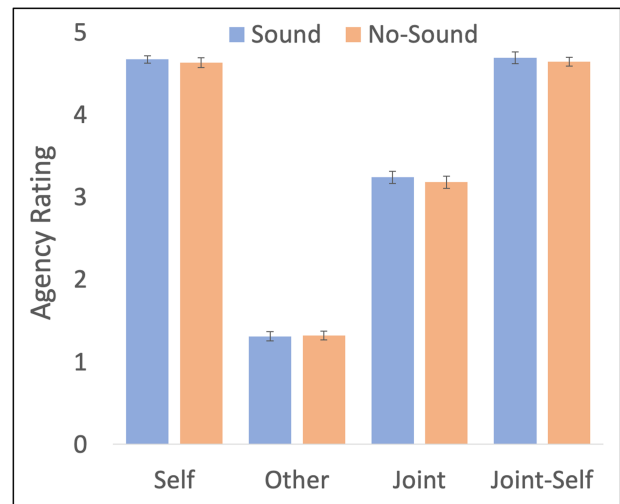

Figure 2. Agency ratings for the four experimental conditions, for both the sound and no sound conditions (error bars represent the standard error).

Results
Agency ratings

Repeated measures ANOVA revealed a significant effect of condition on agency ratings, $F_{(3135)} = 916.16$, $P < .001$, $\eta^2 = 0.95$ but no significant effect of sound, $F_{(1, 45)} = 2.66$, $P = .11$, $\eta^2 = 0.06$, and no sound × condition interaction, $F_{(3135)} = 1.43$, $P = .23$, $\eta^2 = 0.03$. As seen in Fig. 2, agency ratings were highest in the 'self' and 'joint-self' conditions, and lowest in the 'other' condition, with 'joint' falling in between. Paired samples t-tests confirmed that agency ratings were significantly different (at $P < .001$) between all conditions except between the 'self' and 'joint-self' conditions, both for sound trials and non-sound trials.

ERP results
N1

Figure 3 shows the N1 component. Repeated measures ANOVA revealed a significant main effect of electrode, $F_{(8360)} = 17.92$, $P < .001$, $\eta^2 = 0.29$ but no significant effect of condition, $F_{(3135)} = 1.81$, $P = .149$, $\eta^2 = 0.04$, and no significant interaction between condition and electrode, $F_{(241080)} = 0.99$, $P = .475$, $\eta^2 = 0.02$. To assess the probability of the null versus alternative hypothesis, we calculated the Bayes factor (using uninformative priors) for each pairwise comparison between conditions, collapsed across electrodes. This revealed inconclusive evidence for the contrast between the Joint-Self and Other conditions (Bayes Factor (B = 1.35, null versus alternative) as well as between the Joint and Other conditions (BF = 1.89), with all other contrasts showing moderate to strong evidence in favour of the null hypothesis (BFs from 4.32 to 8.64).

An additional exploratory ANOVA was conducted to assess the presence of an N1 (i.e. greater negativity in the sound condition versus the no sound condition). This additional factor was added to the ANOVA above. This revealed a significant main effect of sound, $F_{(1, 45)} = 49.56$, $P < .001$, $\eta^2 = 0.52$, with more negative amplitude in the sound condition (mean = −1.95; std. error = 0.52) compared to the no sound condition (mean = 1.77; std. error = 0.36). This confirmed the presence of an auditory N1 component, as seen Fig. 3b. The absence of any significant effects
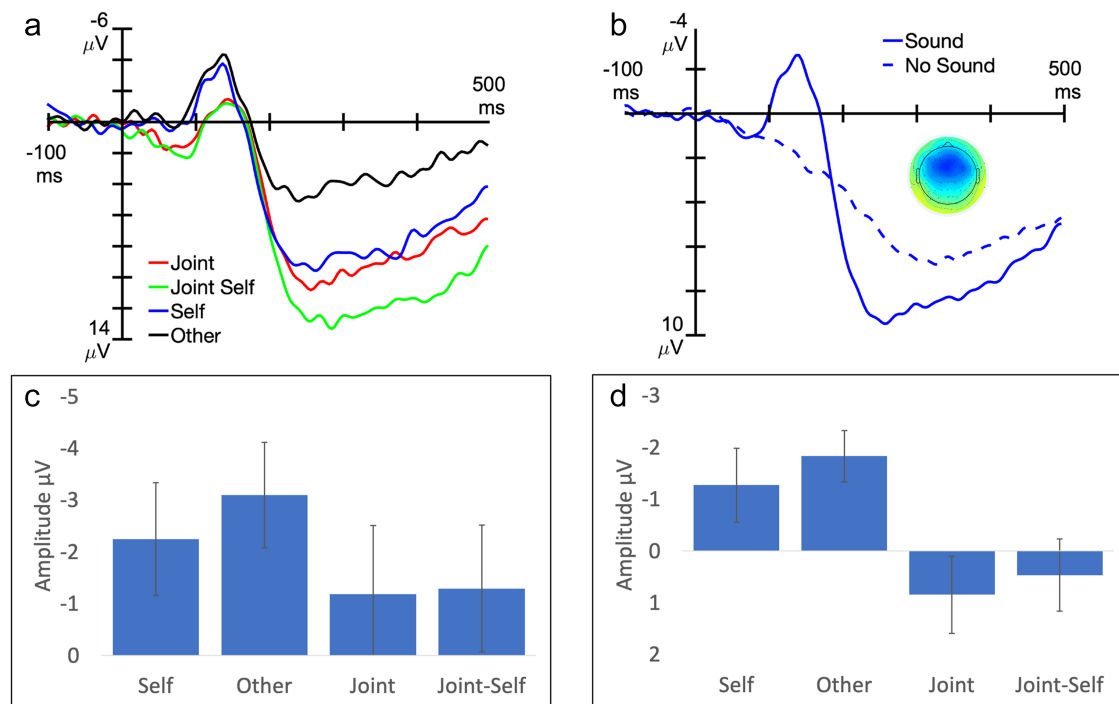
Figure 3. ERP over electrode FCz relative to the onset of the sound. (a) ERP for the four agency conditions for sound trials. (b) Sound and no sound conditions trials collapsed across the agency conditions. The topographic maps show the difference between the sound and no sound conditions in the N1 time window. (c) Average ERP amplitude for the N1 time window and (d) the early N1 time window (error bars represent standard error).

of the condition suggests that this component was not modulated by the agency condition.

A further exploratory analysis was conducted on the early part of the N1. This was defined as the period between the first positive peak and the first negative peak, collapsed across the sound conditions (68–140 ms). This analysis revealed a significant main effect of Condition, $F_{(3135)} = 3.09$, $P = .029$, $\eta^2 = 0.06$, and a significant main effect of electrode, $F_{(8360)} = 10.75$, $P < .001$, $\eta^2 = 0.19$, but no interaction, $F_{(241080)} = 1.05$, $P = .398$, $\eta^2 = 0.02$. Follow-up analysis collapsed across all nine frontocentral electrodes revealed a significant difference between the Other condition and both Joint, $t_{(45)} = 2.54$, $P = .015$, $d = 0.375$, BF $= 0.45$, and Joint-Self conditions, $t_{(45)} = 2.69$, $P = .010$, $d = 0.39$, BF $= 0.33$, while the comparisons between Self and both Joint, $t_{(45)} = 1.49$, $P = .144$, $d = 0.22$, BF $= 3.01$, and Joint-Self, $t_{(45)} = 1.81$, $P = .078$, $d = 0.27$, BF $= 1.85$, conditions were inconclusive. The comparisons between the two joint conditions, $t_{(45)} = 0.37$, $P = .714$, $d = 0.05$, BF $= 8.11$, and between the self and other conditions, $t_{(45)} = 0.87$, $P = .391$, $d = 0.13$, BF $= 6.02$, were strongly in favour of the null hypothesis. These findings suggest that in this early time windows, the N1 differed dependent on whether there was any ambiguity in the source of the action (i.e. joint conditions versus solo conditions).

Tb

Fig. 4 shows the Tb component. Repeated measures ANOVA revealed no significant main effect of electrode, $F_{(1, 45)} = 1.29$, $P = .721$, $\eta^2 = 0.003$, a significant main effect of condition, $F_{(3135)} = 3.78$, $P = .012$, $\eta^2 = 0.08$, and no significant interaction between condition and electrode, $F_{(3135)} = 1.58$, $P = .780$, $\eta^2 = 0.008$. Follow-up tests revealed that the 'Other' condition was significantly different to the 'Self' condition, $t_{(45)} = 2.69$, $P = .015$, $d = 0.4$, BF $= 0.32$, the 'Joint' condition, $t_{(45)} = 3.29$, $P = .002$,

$d = 0.49$, BF $= 0.08$, and the 'Joint-Self' condition, $t_{(45)} = 2.53$, $P = .015$, $d = 0.37$, BF $= 0.5$. All other contrasts showed moderate to strong evidence in favour of the null hypothesis (all BFs from 5.65 to 8.15).

P2

Repeated measures ANOVA revealed a significant main effect of electrode, $F_{(8360)} = 7.23$, $P < .001$, $\eta^2 = 0.14$ as well as a significant main effect of condition, $F_{(3138)} = 3.59$, $P = .015$, $\eta^2 = 0.07$, but no significant interaction between condition and electrode, $F_{(241080)} = 1.30$, $P = .152$, $\eta^2 = 0.03$. Given the absence of a condition by electrodes interaction, we first collapsed across all nine electrodes for each condition. As seen in Fig. 5, P2 amplitude appeared significantly reduced for the 'Other' condition compared to 'Self', 'Joint', and 'Joint-Self'. This was confirmed by paired samples t-tests, which revealed significant differences between the 'Other' condition and 'Self' ($t_{(45)} = 2.89$, $P = .006$, $d = 0.43$, BF $= 0.20$), 'Joint' ($t_{(46)} = 2.25$, $P = .030$, $d = 0.33$, BF $= 0.84$), and 'Joint-Self' ($t_{(46)} = 3.02$, $P = .004$, $d = 0.45$, BF $= 0.15$). All other contrasts were nonsignificant (all ts <1), showing strong support for the null hypothesis (BFs from 6.95 to 8.56). These findings suggest that P2 amplitude appears to be moderated by whether or not the participant was at all involved in moving the planchette but does not distinguish between situations where the participants have some control versus complete control over the planchette.

To further investigate the link between agency experience and the P2 component, we correlated agency ratings with P2 amplitude across all sound trials for each participant. When including all sound trials, irrespective of agency condition, the mean correlation across participants was 0.11 (SD $= 0.15$), which was significantly greater than zero ($t_{(45)} = 4.97$, $P < .001$, $d = 0.73$). When conducting this analysis within conditions, no significant correlations emerged (all ts < 1).
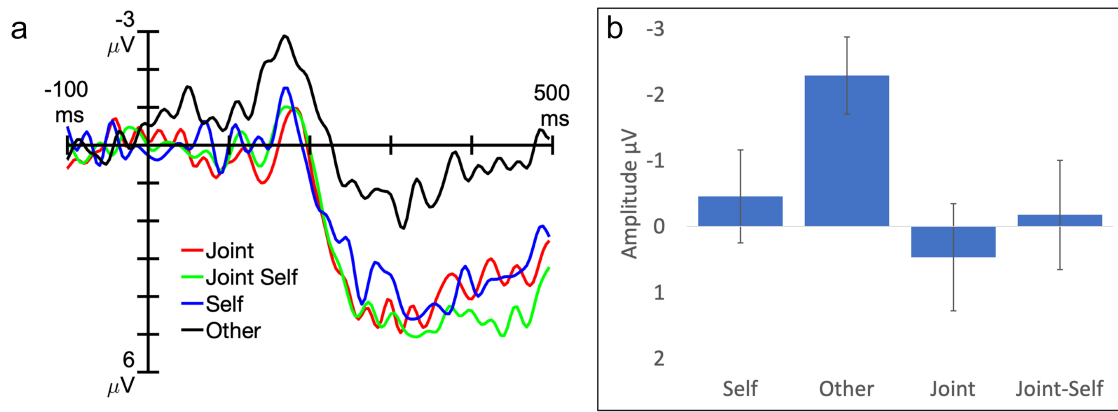
Figure 4. (a) ERP for the Tb component for the four agency conditions and (b) average ERP amplitude for Tb component (error bars represent standard error).
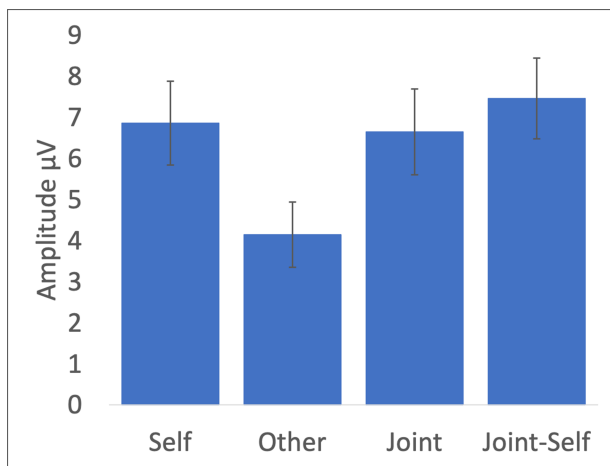

Figure 5. Average ERP amplitude for P2 component (error bars represent standard error).

Discussion

The current study investigated the neural mechanisms of agency processing in the Ouija board task. Agency ratings confirmed that our manipulation was largely successful in modulating the experience of agency between conditions in that participants experienced most agency in the 'self' condition and least agency in the 'other' condition, with the 'joint' condition between the two. However, the 'joint-self' condition did not differ significantly from the 'self' condition. This suggests that in our study participants were able to determine that they had complete control over the movements of the planchette in this condition, despite them being in the context of a joint action block. This finding is in contrast to some previous studies (e.g. Beyer et al. 2017, Schwarz et al. 2023), which have observed that agency experience can be modulated in joint action contexts, with only minimal influence of a coactor. However, these studies used somewhat different manipulations and also had outcomes that were linked to monetary reward, which are known to influence both agency experience and neural processing of action feedback (e.g. Li et al. 2010, Beyer et al. 2017, Hassall et al. 2019).

We found that the amplitude of the N1 component did not significantly differ as a function of agency condition, despite the fact that a clear N1 was present (as evidenced by the difference

in amplitude between the sound and no sound condition). This is in contrast to Loehr et al. (2013) who showed reduced sensory attenuation to jointly triggered action outcomes compared to self-generated action outcomes. As noted in the introduction, one important difference in our study is that temporal prediction of the sound was more tightly controlled across conditions. Similar to Han et al. (2021), we also did not observe any difference in N1 amplitude between the active (self) and passive (other) conditions in our study, suggesting that N1 attenuation does not differentiate between self and other generated stimuli, when these are matched for temporal predictability.

Our exploratory analysis revealed significant modulation of the early part of the N1 component based on agency condition. In this period, the N1 differed between the joint action conditions and the solo action conditions. Thus, rather than reflecting the attenuation of self-generated sounds, this was modulated by the degree of ambiguity in the control of the action. Perhaps surprisingly, this component was reduced in the ambiguous conditions, where one might expect a more focused processing of the action outcome, in order to help ascribe agency. One possibility is that this reflects modulation of the early P50 component in response to the sound rather than the N1. This component has been observed to be reduced to the second stimulus when presenting paired auditory stimuli and has been related to sensory gating, with this difference reduced in patients with schizophrenia (Freedman, et al. 2020). In the current study, this might reflect decreased processing of the sound in situations of greater certainty regarding the cause of the action outcome. However, given that this analysis was not preregistered, future research should aim to explore this possibility further.

The later modulations of the Tb and P2 components showed a different pattern, differentiating between the condition where the participant had no control of the action (the 'Other' condition), and all three conditions where participants had at least some control over the action. These modulations are in line with those observed in Han et al. (2021) who observed an attenuated Tb and increased P2 amplitude in their 'active' condition, where participants had agency over the sounds, compared to the 'passive' condition where the computer controlled whether the sound played or not. Our exploratory analysis revealed that across conditions, trials with a larger P2 amplitude were associated with increased self-reported agency. This provides some evidence towards the possibility that the P2 might be a neural marker of sense of agency.

However, it is important to note that P2 amplitude did not differ between the 'self' condition and either the 'joint' condition or the 'joint-self' condition. This was despite the fact that experienced agency did differ between 'self' and 'joint' conditions. As such, these findings suggest that the P2 does not reflect subtle differences in experienced agency in joint action. This is also backed up by the lack of clear correlations between individual trial P2 amplitude and agency ratings, within each of the agency conditions, although note that the absence of such a correlation might also reflect a lack of power due to noise in both individual trial ERPs and in subjective agency reports. Nonetheless, the overall correlation across trials likely reflects the difference in agency experience between conditions rather than subtle variations within conditions.

The current experiment employed a rather different paradigm to most agency studies, which tend to focus on simple actions, such as button presses, and the sensory consequences of those actions. While this might add to the ecological validity of our study, it also means that individual trials lasted much longer and involved more complex movements. This may have had the effect of both increasing variability in the EEG signal and also reducing the number of trials that could reasonably be included, and therefore reducing power to detect differences. Additionally, it appears that our manipulation was not successful in convincing participants that their coactor truly influenced the movements in the joint-self trials, limiting the usefulness of this condition.

Notwithstanding these limitations, this study provides new insight into the neural and cognitive mechanisms involved in agency attribution in joint action contexts. The absence of N1 attenuation provides further evidence to dissociate this phenomenon from an experienced agency. Given that N1 attenuation is typically interpreted to reflect motor-prediction mechanisms, our findings argue again the role of these processes in agency attribution. The modulation of the early N1/P50 component in our study suggests that early sensory gating mechanisms may vary dependent on the degree to which sensory processing might help to disambiguate agency. The fact that we do not see a single ERP component that covaries with experienced agency suggests that agency attribution is an iterative process. In our study, while early components differentiated based on ambiguity (solo versus joint action contexts), later components differentiated based on no-agency versus some or complete agency. Indeed, these modulations may reflect attentional processes associated with agency attribution rather than the neural signatures of agency processing per se.

Acknowledgements

Author contributions

Gethin Hughes (Conceptualization, Funding acquisition, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft, Project administration) and

Peter Leslie Thomas Gooding (Conceptualization, Investigation, Funding acquisition, Methodology, Visualization, Writing—review & editing, Project administration, Software)

Conflict of interest: The authors declared that they had no conflict of interest with respect to their authorship or the publication of this article.

Funding

Data availability

Data for each of the analyses outlined in the paper are available on the Open Science Framework (https://osf.io/vp9hf/).

References

Beyer F, Sidarus N, Bonicalzi S et al. Beyond self-serving bias: diffusion of responsibility reduces sense of agency and outcome monitoring. *Soc Cogn Affect Neurosci* 2017;**12**:138–45. https://doi.org/10.1093/scan/nsw160

Blakemore SJ, Wolpert D, Frith C. Why can't you tickle yourself? *Neuroreport* 2000;**11**:R11–6. https://doi.org/10.1097/00001756-200008030-00002

Blakemore SJ, Wolpert DM, Frith CD. Abnormalities in the awareness of action. *Trends Cognit Sci* 2002;**6**:237–42. https://doi.org/10.1016/S1364-6613(02)01907-1

Bolt NK, Loehr JD. Sensory attenuation of the auditory P2 differentiates self- from partner-produced sounds during joint action. *J Cogn Neurosci* 2021;**33**:2297–310. https://doi.org/10.1162/jocn_a_01760

Delorme A, Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods* 2004;**134**:9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dewey JA, Knoblich G. Do implicit and explicit measures of the sense of agency measure the same thing? *PLoS One* 2014;**9**:e110118. https://doi.org/10.1371/journal.pone.0110118

Freedman R, Olsen-Dufour A MOlincy A. P50 inhibitory sensory gating in schizophrenia: analysis of recent studies. *Schizophrenia Research* 2020;**218**:93–98. https://doi.org/10.1016/j.schres.2020.02.003

Grunbaum T, Christensen MS. Measures of agency. *Neurosci Conscious* 2020;**2020**:niaa019. https://doi.org/10.1093/nc/niaa019

Haggard P. Sense of agency in the human brain. *Nat Rev Neurosci* 2017;**18**:196–207. https://doi.org/10.1038/nrn.2017.14

Han N, Jack BN, Hughes G et al. Sensory attenuation in the absence of movement: differentiating motor action from sense of agency. *Cortex* 2021;**141**:436–48. https://doi.org/10.1016/j.cortex.2021.04.010

Harrison AW, Hughes G, Rudman G et al. Exploring the internal forward model: action-effect prediction and attention in sensorimotor processing. *Cereb Cortex* 2023;**33**:9130–43. https://doi.org/10.1093/cercor/bhad189

Hassall CD, Hajcak G, Krigolson OE. The importance of agency in human reward processing. *Cognit Affect Behav Neurosci* 2019;**19**:1458–66. https://doi.org/10.3758/s13415-019-00730-2

Hughes G, Desantis A, Waszak F. Mechanisms of intentional binding and sensory attenuation: the role of temporal prediction, temporal control, identity prediction, and motor prediction. *Psychol Bull* 2013;**139**:133–51. https://doi.org/10.1037/a0028566

Li P, Jia S, Feng T et al. The influence of the diffusion of responsibility effect on outcome evaluations: electrophysiological evidence from an ERP study. *Neuroimage* 2010;**52**:1727–33. https://doi.org/10.1016/j.neuroimage.2010.04.275

Loehr JD. Sensory attenuation for jointly produced action effects. *Front Psychol* 2013;**4**:172. https://doi.org/10.3389/fpsyg.2013.00172

Luck S J, Gaspelin N. How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology* 2017;**54**:146–157. https://doi.org/10.1111/psyp.12639

Schwarz KA, Tonn S, Buttner J *et al*. Sense of agency in social hierarchies. *J Exp Psychol Gen* 2023;**152**:2957–76. https://doi.org/10.1037/xge0001426

Synofzik M, Vosgerau G, Newen A. I move, therefore I am: a new theoretical framework to investigate agency and ownership. *Conscious Cogn* 2008;**17**:411–24. https://doi.org/10.1016/j.concog.2008.03.008

Waszak F, Cardoso-Leite P, Hughes G. Action effect anticipation: neurophysiological basis and functional consequences. *Neurosci Biobehav Rev* 2012;**36**:943–59. https://doi.org/10.1016/j.neubiorev.2011.11.004

Wegner DM. *The Illusion of Conscious Will*. Cambridge, MA: MIT Press, 2002.

Wegner DM, Wheatley T. Apparent mental causation: sources of the experience of will. *Am Psychol* 1999;**54**:480–92. https://doi.org/10.1037/0003-066X.54.7.480

Weller L, Schwarz KA, Kunde W *et al*. Was it me? – filling the interval between action and effects increases agency but not sensory attenuation. *Biol Psychol* 2017;**123**:241–9. https://doi.org/10.1016/j.biopsycho.2016.12.015

Wolpert DM, Ghahramani Z, Jordan MI. An internal model for sensorimotor integration. *Science* 1995;**269**:1880–2. https://doi.org/10.1126/science.7569931