Consciousness and Cognition 119 (2024) 103667

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/yccog

More than fulfilled expectations: An electrophysiological investigation of varying cause-effect relationships and schizotypal personality traits as related to the sense of agency

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ARTICLE INFO

Keywords:
N100
Forward model
Comparator model
Sensory attenuation
Sense of agency
Schizotypal personality traits
Readiness potential

ABSTRACT

The sense of agency (SoA) is central to human experience. The comparator model, contrasting sensory prediction and action feedback, is influential but limited in explaining SoA. We investigated mechanisms beyond the comparator model, focusing on the processing of unpredictable stimuli, perimotor components of SoA, and their relation to schizotypy.

ERPs were recorded from 18 healthy participants engaged in button-pressing tasks while perceiving tones with varying causal relationships with their actions. We investigated the processing of non-causally related tones, contrasted this to causally related tones, and examined perimotor correlates of subjective expectancy and experience of agency.

We confirmed N100 attenuation for self-generated stimuli but found similar effects for expectancy-dependent processing of random tones. SoA also correlated with perimotor ERP components, modulated by schizotypy.

Thus, neural processes preceding actions contribute to the formation of SoA and are associated with schizotypy. Unpredictable events also undergo sensory attenuation, implying additional mechanisms contributing to SoA.

1. Introduction

1.1. Phenomenology of sense of agency

How we experience ourselves as actors of our actions, and their effects on the environment is an important aspect of the self. From a phenomenological perspective, the self is seen as “an integrated part of our conscious life, which has an immediate experiential reality” (Zahavi, 2003, p. 59). Therefore, the sense of agency (SoA), which refers to the experience of the self as an agent of an action, is a basic pre-reflective component of self-experience. To illustrate this, consider the act of ringing a doorbell at a friend’s house. It is unusual for individuals to question their own role in pressing the doorbell and consequently setting off the ringing sound.

A two-step account of agency presented by Synofzik et al. (2008) distinguishes bottom-up and top-down contributions to the SoA.

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https://doi.org/10.1016/j.concog.2024.103667
Received 5 July 2023; Received in revised form 28 December 2023; Accepted 12 February 2024
Available online 29 February 2024

They argue that SoA consists of the feeling of agency and the judgment of agency. While the former is defined as a non-conceptual, low-level feeling of being the agent of an action, the latter refers to an explicit judgment of being the agent (Synofzik et al., 2008). How these two steps contribute to the SoA depends on the task and context (Synofzik et al., 2008). Synofzik et al. (2008) suggest that, in daily life, we largely rely on the feeling of agency and do not need to make explicit judgments about our agency.

In line with this two-step account, Gallagher distinguishes between two contiguous parts of the SoA. Attribution of agency (also called *reflective* SoA) refers to the act of attributing a specific action to oneself. From a phenomenological perspective, the attribution or explicit judgment of agency follows a more basic experience of the self—the experiential or *pre-reflective* SoA (Gallagher & Zahavi, 2008). The latter part of agency is inherent in a so-called *minimal self*, which refers to the conscious experience of oneself as a direct subject (Gallagher, 2000). Therefore, the pre-reflective SoA does not entail a reflective act of consciousness but results from an immediate first-person experience of being the cause of events. It is defined as "the pre-reflective experience or sense that I am the *author* of the action" (Gallagher & Zahavi, 2008, p. 161).

1.2. Forward models

One influential approach to explaining the SoA is based on assumptions of the motor control system. Forward models, categorized as internal models of the motor control system, propose that individuals employ motor commands or intentions to predict their sensory consequences, thereby allowing for a distinction between self-generated events (own actions) and non-self-generated events (Wolpert, 1997; Wolpert et al., 1995). Thus, forward models represent causal relationships between actions and their predicted outcomes (Wolpert, 1997). Before the execution of any motor *action*, a motor *command* is generated and an efference copy of the motor command is produced (von Holst, 1954). This efference copy predicts the sensory outcomes of the action using a forward model mechanism (i.e., corollary discharge; Sperry, 1950). Some authors (e.g., Frith et al., 2000) employ the terms "efference copy" and "corollary discharge" interchangeably. However, we assume that the corollary discharge of a sensory outcome belonging to a motor action occurs *after* an efference copy of a motor plan is generated. By comparing the predicted sensory outcomes with the sensory feedback received, it is possible to distinguish the sensory effects of own movements from those that are not self-caused. The sensory feedback of own movements is called reafference (von Holst, 1954) and when this is congruent with a matching efference-copy, sensory effects of self-movements are suppressed. In other words, through reafference processes, the sensory effects of self-movements are canceled out (Wolpert, 1997). Additionally, forward models can provide information regarding the predicted outcomes that is used before sensory feedback becomes available to maintain perceptual stability (Miall et al., 1993; Wolpert, 1997).

1.3. The comparator model

In SoA literature, these conclusions drawn from the motor control system are also included in the comparator model (Haggard, 2017; Moore, 2016). The experience of being the agent of a movement and the associated outcomes is elicited when there is a match between the predicted sensory feedback of a motor action, generated by a forward model, and the actual sensory feedback generated by the movement (Haggard, 2017). Hence, self-generated sensations can be accurately predicted, owing to the availability of an efference copy for comparison (Frith et al., 2000). By contrast, externally generated sensations lack an efference copy, rendering such a comparison unfeasible.

One well-known consequence of the successful prediction of sensory feedback is sensory attenuation. Sensory attenuation assumes that sensory reafferences of correctly predicted sensory consequences are attenuated. There is evidence that sensory predictions in healthy individuals lead to perceptual attenuation of self-produced stimulation. For example, research has demonstrated that participants rate self-generated tactile stimuli as less tickly and intense than sensations elicited by similar external stimuli (Blakemore et al., 1999). With the addition of a delay to self-generated stimuli, Blakemore et al. (1999) demonstrated that delayed sensory feedback led to increased ticklishness. Therefore, they suggested that perceptual attenuation is due to a precise forward model and that the amount of sensory attenuation depends on the deviation between sensory feedback and the prediction of the model.

1.4. Electrophysiology of sense of agency

An important part of the empirical support for these models of the SoA has been based on the study of sensory attenuation using electrophysiological data. Solid evidence of this attenuated sensation of self-generated stimuli was found in N100 event-related potentials (ERPs). In the auditory-speech domain, several studies have shown that the N100 for self-generated speech is attenuated compared to playback of one's own speech or altered or alien auditory feedback (Bühler et al., 2016; Heinks-Maldonado et al., 2005; Whitford, 2019). Another important example is the non-speech motor-auditory domain. Parallel to the former experiments with speech, it was found for non-verbal sounds that lower N100 amplitudes were elicited by self-generated sounds than by externally produced sounds (Baess et al., 2008, 2011; Schafer & Marcus, 1973; Timm et al., 2014). According to findings by Baess et al. (2011), sensory attenuation persists even when random sounds are interspersed among self-generated sounds. Given the consistent correlations between the subject's causal role in events and the sensory attenuation observed in the perception of these events, sensory attenuation can be considered a reliable indicator of biological processes that represent the subject's SoA through forward models. It is also important to note here that there is also evidence for electrophysiological correlates of agency that is not related to the sensory feedback, such as alterations of the lateralized readiness potential (Ford et al., 2014, Vercillo et al., 2018).

1.5. Disruption of sense of agency

When it comes to the assessment of the experiential role of the SoA, the importance of these processes for our sense of self becomes apparent because of the drastic consequences that occur when these mechanisms fail and the SoA is disrupted. Such effects are referred to as ego disturbances, including symptoms such as depersonalization, alienation, passivity, thought insertion, thought withdrawal and thought broadcasting. These symptoms are typically found in psychotic disorders. As explained by Moore (2016), specific problems with sensorimotor prediction are present in schizophrenia. In patients with schizophrenia, an abnormal experience of agency might be the neuropathological basis for positive symptoms (hallucinations and delusions). Passivity symptoms, which are included in the positive symptom category, are an excellent example of what happens when SoA is impaired. Mellor (1970) reported the following statement from a patient with passivity symptoms: "It is my hand and arm which move, and my fingers pick up the pen, but I don't control them. What they do is nothing to do with me" (p. 18). Returning to our doorbell example, a person with a distorted SoA may argue that it was his or her finger moving but would not experience control over the movement and, thus, would not feel responsible for the ringing.

Evidence for disrupted SoA in individuals with psychotic disorders has been reported by Blakemore et al. (2000). They reported on patients with auditory hallucinations and passivity experiences who were able to tickle themselves. This indicated that the movement-associated sensory feedback did not match the predictions in these patients. Therefore, the feedback was unexpected, and no sensory attenuation occurred. Thus, the sensation was not perceived as internally generated but as coming from an external stimulus and manifested itself as tickling. Physiologically, there is evidence of a lack of sensory attenuation and thus impaired SoA in patients with schizophrenia. Concerning N100 attenuation as an indicator of the SoA, several studies reported that patients with schizophrenia and schizoaffective disorder showed no attenuated N100 for self-generated auditory sensory feedback (Ford et al., 2001, 2014; Heinks-Maldonado et al., 2007).

1.6. Challenges to existing models

While forward models provide good explanations for many empirical observations such as the relationship between sensory attenuation, SoA, and important dimensions of ego disturbances, we believe that they may be insufficient for a fully functional account of the mechanisms underlying SoA. First, patients with ego disturbances frequently have a false-positive SoA; that is, they experience themselves as causing events when such causation is implausible (or even impossible). This is for example the case when a patient tells that because they press the light switch, it starts snowing outside. Other examples of disturbance in the SoA outside the psychotic symptoms can be found in patients with phantom limbs (for a review on phantom limbs see Ramachandran & Hirstein, 1998) or while dreaming. In these cases, however, it is unclear how a comparator model can account for false-positive experiences of one's own agency (see also Carruthers, 2012 for such attempts). Second, if we consider Gallagher's description of a minimal self, which is not further reducible (Gallagher, 2000), and if the SoA is a fundamental constituent of this minimal self, this implies that individuals must possess an understanding of themselves as agents before experiencing the consequences of their actions. Again, such an a priori understanding of SoA would not be explainable by a comparator model because it would precede, and therefore be independent of, the eventual sensory consequences of the subject's actions.

1.7. Current study

In this study, we investigated the features of the SoA that go beyond the comparator model using an electrophysiological approach. In particular, with regard to the point that the comparator model cannot explain well that there are cases of false-positive SoA, we were interested in the behavioral and electrophysiological correlates of subjective expectancy and experience of agency in the sensory processing of events not caused by the subject. Regarding the point that there must be an a priori SoA we were interested in electrophysiological correlates of subjective expectancy and experience of agency during moments when the subject was actively engaged as an agent, that is, at movement onset. Therefore, we conducted an experiment in which the subjects spontaneously pressed a button and perceived auditory stimuli that were in varying causal relationships to these button presses. Thus, using this design we were able to manipulate the causal relationship between action and perception. We expected that this manipulation of the causal relationship between action and perception would systematically alter subjects' SoA. This would allow us to study the correlates of SoA a) in stimuli not caused by the subject and b) at movement onset. In our analysis, we propose the following hypotheses:

The first part of our work focused on the N100 to investigate whether our experimental manipulation of the SoA was successful, and to confirm previous findings. According to the literature, the N100 in healthy subjects is attenuated for self-generated auditory feedback compared to passive listening to the same stimulus (Baess et al., 2008, 2011). Consequently, our primary hypothesis (H1) was that self-generated sounds would elicit a smaller amplitude in auditory N100 than passive listening to sounds. Additionally, we hypothesized that an increase in SoA would correspond to a decrease in the N100 amplitude, specifically in the case of self-made sounds.

Regarding our second hypothesis (H2), which suggests that the SoA is already represented at the moment of action, there is supporting evidence from electrophysiological studies. These studies have shown that the expectancy of a stimulus can modulate premotor brain activity. In a visuomotor paradigm, Vercillo et al. (2018) observed a more negative late readiness potential (RP) where motor action leads to a visual stimulus, compared with the RP preceding the same motor action alone. Similarly, Ford et al. (2014) reported a larger lateralized RP preceding button presses that resulted in a tone compared with the lateralized RP preceding button presses without an associated tone. Notably, they found a relationship between a larger lateralized RP preceding motor action and greater suppression of the N100 amplitude. Based on these findings, we assumed that the subjective agency rating and our manipulations of the SoA would affect neural activity before and during motor action, rather than solely influencing sensory feedback.

Our third hypothesis (H3) focused on the processing of sounds that were not caused by the subjects' button presses. If the concept of false-positive SoA existed, we anticipated finding correlations between the participants' expectancy and their rating of agency, and the processing of these randomly occurring sounds. Interestingly, in an audiomotor task, Moore et al. (2009) demonstrated how priming with random sounds has an effect on SoA of subsequent sounds, when these are not triggered by the subject. The effect, however, is dependent on the temporal correlation between the stimuli. This suggests a modulation of SoA though external cues, when internal motor cues are not available. Thus, we hypothesized that the manipulation of the SoA and explicit subjective agency ratings were related to the processing of randomly occurring stimuli.

Finally, SoA is a core element of self-experience and the self. Disturbances in SoA have been linked to ego disturbances and various psychotic symptoms. Taking a dimensional approach to psychotic symptoms (Guloksuz & van Os, 2018), schizotypy is viewed as a continuously distributed trait among the general population and high levels of schizotypy can be related to disorders within the schizophrenia spectrum (Claridge & Beech, 1995; Nelson et al., 2013). Since our study focused on healthy individuals, we expected (H4) variations in the levels of schizotypal personality traits and hypothesized that these traits would be related to the behavioral and neurophysiological correlates of SoA, as investigated in H1–3.

2. Material and methods

2.1. Participants

Eighteen healthy individuals took part in the study (10 women, 8 men; age range = 18–39 years, $M = 22.89$, $SD = 4.68$). Seventeen undergraduate psychology students participated as part of their curriculum in the Faculty of Psychology at the University of Bern. One participant volunteered to participate in the study. All the participants had normal or corrected-to-normal vision and spoke standard German or Swiss German. Normal hearing was assessed using the Whispered Voice Test (Pirozzo et al., 2003). Individuals with neurological or psychiatric diagnoses or with diagnosed first-degree relatives were excluded. None of the participants had been in a substance-induced state of intoxication for at least seven days before the recording session. The participants were not paid for their participation, but study credits were granted to the undergraduate psychology students. Informed consent was obtained from all participants before the start of the study. The study was conducted at the vonRoll University Center in Bern, was approved by the Ethics Commission of the University of Bern and met all the requirements of the Declaration of Helsinki. Participants provided demographic data and were asked to complete the German version of the Schizotypal Personality Questionnaire (SPQ-G; Klein et al., 1997).

2.2. Electrophysiological recordings

Electrical brain activity was measured using a 64-channel ActiCap system (Brain Products GmbH, Gilching, Germany; plus one reference and one ground electrode) mounted in an electrode cap according to the international 10–20 system. Electroencephalography (EEG) recordings were obtained using BrainAmp DC amplifiers and the BrainVision Recorder (Brain Products GmbH, Gilching, Germany). Impedances of the electrodes were kept below 20 kΩ, and FCz was used as the recording reference. The data was sampled with 500 Hz. All EEG recordings were conducted in an electrically and acoustically shielded, dimly lit cabin. To preserve the EEG data quality, the participants were instructed to move and blink as little as possible during the recording, placed their chin on a chin rest, and looked at a fixation cross at the center of the screen during the blocks.

2.2.1. Resting EEG

A resting EEG was recorded to optimize the preprocessing of the experimental EEG data, both with open eyes, closed eyes, and during eye movements. The participants then performed a trial of the experimental task without EEG recording, before starting the experimental protocol.

2.3. Experimental protocol

2.3.1. Control tasks

After practicing, the EEG recording was started, and the participants completed two control tasks. In the first control task, participants listened to sounds (*beep-only*; 0.3 s, 440 Hz (A), and 80 dB). The interval between these sounds varied randomly from 3 to 5 s. In the second control task, the participants were instructed to press a button approximately every 3–5 s in a randomized manner. The control tasks consisted of 30 trials each (30 sounds and 30 button presses).

2.3.2. Experimental task

In the experimental task, the participants were instructed to press a button with the index finger of their dominant hand every 3–5 s in a randomized manner. No predictable pattern should occur within button presses. By pressing the button, participants could eventually trigger sounds (*self-made sound* = 0.3 s, A, 80 dB) with varying delay and probability. Identical sounds could also occur that were not caused by participants (*random sound* = 0.3 s, A, 80 dB). All sounds were presented in blocks of 10 button presses. Within each block, the probability and delay of self-made sounds were approximately fixed. The self-made sounds had a delay of either 200, 500, or 800 ms, with a random variance of up to 500 ms for each delay. The blockwise probabilities of the self-made sounds were 0.25, 0.50, 0.75, or 1.00. The probability of random sounds was inversely proportional to the block's probability of the self-made sounds such that the sum of the two probabilities was always one. The timing of the random sounds was adapted to match the participants' behavior based on the timing of the average interval of the last 10 button presses. To assess the subjective experience of SoA, participants were instructed to promptly rate the question "Did you cause the sounds?" after every block on a 7-point Likert scale (1 = *I do not agree at all.* to 7 = *I fully agree.*). After the rating, the participants could take a self-paced pause before the next block.

The combination of all delays and probabilities yielded twelve different block types. Each block type was presented three times, yielding 36 blocks. The blocks were presented in random order. On average, the participants took approximately 2 h to complete the entire experiment.

During the experimental task, the participants viewed a computer monitor (21.26 in, 103 cm viewing distance) with a fixation cross. The instructions, presentation of sounds, and collection of responses were implemented using Psychopy (Peirce et al., 2019).

See Fig. 1 for a visual representation of the task design.

2.3.3. *Data preprocessing*

The EEG data were preprocessed using the Brain Vision Analyzer 2.2 (Brain Products GmbH, Gilching, Germany). First, in the resting EEG data, channels with poor or absent EEG signals were interpolated using spherical splines when necessary. After bandpass filtering of the data (1–20 Hz, Notch Filter 50 Hz), we performed an Independent Component Analysis (ICA). The resulting ICA components were visually inspected to identify eye movement and heartbeat artifacts and to construct a spatial filter matrix that eliminated the identified components for each participant. Next, we applied this spatial filter to the temporally unfiltered task data of each participant after interpolating bad channels. Finally, we manually identified and excluded any remaining artifacts. The data were then re-referenced to the average reference and bandpass-filtered from 0.3 to 7 Hz, with an additional 50 Hz Notch Filter to suppress line noise that may have leaked through the bandpass filter. Finally, continuous EEG recordings were segmented based on the markers into epochs from −500 to 200 ms for motor-evoked potentials (MEPs) and from 0 to 500 ms for auditory-evoked potentials (AEPs).

2.4. *Analysis of behavioral data*

We analyzed the effects of delay, probability, and SPQ-G scores on subjective agency ratings with a linear mixed model using the R package *lme4* (Bates et al., 2015). We included delay, probability, SPQ-G scores, and associated interactions as fixed-effect factors and participants as random-effect factors.

2.5. *Analysis of evoked potentials*

An overview of the analysis strategies employed to test our different hypothesis is shown the Fig. S2 of the supplementary material.

2.5.1. *Evoked potentials*

Grand mean AEPs were computed separately for each sound type (beep-only, self-made sound, and random sound) and each subject. For the button press, we calculated the MEP grand mean for each subject. The average included trials per subject were 27.9 (SD = 1.8) for the beep-only condition, 217.2 (SD = 12) for the self-made sound condition, 103.1 (SD = 46.9) for the random sound condition and 374.7 (SD = 15.0) for the button presses. Finally, the grand mean MEP and AEP for each sound type across all subjects were computed.

2.5.2. *Microstate analysis*

We performed microstate analyses to define the time windows for the ERP components and thereby reduce the number of statistical tests (Koenig & Pascual-Marqui, 2009). These analyses were conducted using the grand mean MEP and AEP across all subjects. Microstates are short time windows of quasi-stable topographic configurations (topographies) that are assumed to reflect different stimulus processing steps (Habermann et al., 2018). The identification of microstates as periods of quasi-stable topographies justifies averaging within the time window of a given microstate. Given the assumption that the source configuration remains highly stable

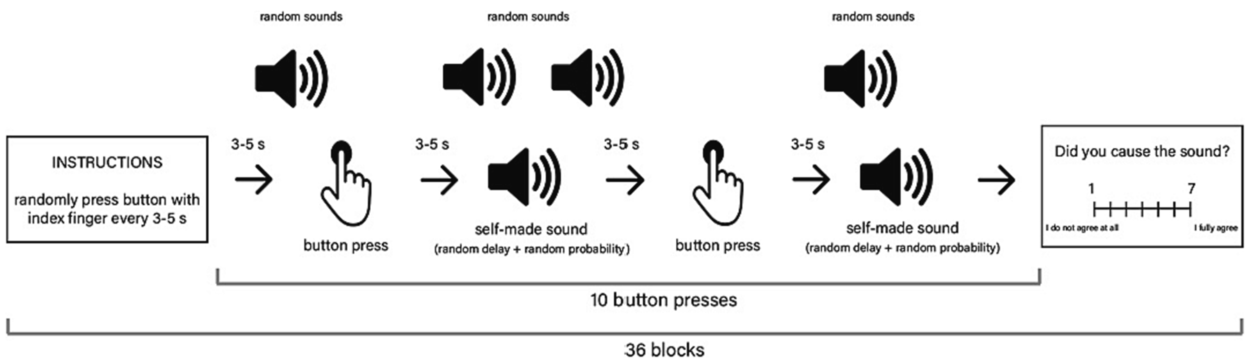

Fig. 1. *Experimental Task Design.* Note: s = seconds.

during this timeframe, it is reasonable to regard all data within this period as a single component and collapse them (Koenig & Pascual-Marqui, 2009). Consequently, every microstate indicates spatially different neural activity.

An important parameter in the microstate analysis is the number of microstates. As our main focus was on robustly identifying the perimotor MEP and early post-stimulus AEP components, we generated microstate models of the data using various numbers of clusters. We then carefully selected the final microstate model for the MEP and AEP, which consistently captured these components, regardless of the addition or removal of a microstate. In other words, we ensured that the selected model remained highly similar to the models obtained with one additional or one fewer microstate class.

2.5.3. Covariance analysis

To analyze the effects of our experimental manipulations and subjective agency ratings on event-related EEG potentials, we conducted regression analyses at the single-trial level. Therefore, we created the predictor *delay*, *probability*, and *subjective agency rating* for each trial and subject according to the experimental design and subject's ratings. We then conducted a covariance analysis of the single-trial MEPs and AEPs with these three predictors by computing the weighted averages of the single-trial data, where the weighting of these averages stemmed from the predictors (Koenig et al., 2008). For each subject, this yielded the scalp fields of the sources that linearly covaried with the given predictors. The obtained covariance maps were averaged over time for each microstate component. Computing such covariance maps is mathematically equivalent to computing difference maps between category-wise individual mean ERP map series, with the exception that the experimental variable is assumed to be a linear instead of a categorical predictor of the variance in the ERPs and that, therefore, estimates of slopes instead of estimates of differences are obtained. For visualization, specific ERP traces for the stratified predictors were computed and presented in the supplementary material (Fig. S3).

2.5.4. Null-hypothesis testing of the covariance maps using the Topographic Consistency test

Next, to establish the significance of the above covariance analyses, we tested the across-subject mean covariance maps against the null hypothesis that these mean maps would not be systematically different from an all-zero, "flat" map. In order to avoid problems of multiple testing across electrodes, we employed a technique known as Topographic Consistency Test (TCT) (Koenig & Melie-García, 2010). As a measure of spatial consistency across subjects, the TCT uses the Global Field Power (GFP) of the grand mean MEPs, AEPs, and covariances. To statistically test the GFP of our experimental data, the TCT drew instances of GFP under the null hypothesis by computing the GFP values after randomly shuffling the channel assignments of the data per subject before averaging across subjects. The significance of the TCT was then defined as the percentage of cases in which the GFP under the null hypothesis was equal to or larger than the GFP of the experimental data and yielded evidence of consistent activation of neural sources across subjects (Koenig & Melie-García, 2010). For our data, TCTs were conducted for the components obtained from the microstate analysis and by drawing 5000 samples for the null hypothesis.

2.5.5. TANOVA in microstates

In addition to examining consistency across subjects, we were also interested in eventual topographic differences in ERP and covariance maps as a function of experimental conditions and predictors. To test such map differences, we used a randomization procedure called Topographic Analysis of Variance (TANOVA). In general, in TANOVA, condition-wise grand means are computed across subjects and compared using a single overall index of topographic difference between the conditional mean maps (Koenig & Pascual-Marqui, 2009). To test the index of the map difference for significance, it was compared with the distribution of the same index under the null hypothesis. To compute this, the TANOVA uses randomization statistics. Therefore, the topographies of the subjects were randomly shuffled between conditions and averaged across the subjects for each condition. The index of the map difference was then recomputed using the randomized data. This randomization procedure was repeated 5000 times to obtain a proper estimate of the null hypothesis distribution (Habermann et al., 2018). The significance of the differences between the conditions was then estimated by comparing the distribution of the index under the null hypotheses and the index obtained from the observed data. For our final analysis, we included SPQ-G as a between-subjects factor. In this case, TANOVA used the GFP of the covariance map for the SPQ-G across subjects as an index of the size of the effect. For the randomization procedure, the subjects' covariance maps and their SPQ-G scores were randomly swapped, and GFP was computed for these data. This procedure was repeated 5000 times to estimate the distribution of GFP under the null hypothesis. The observed GFP was then compared to the GFP distribution under the null hypothesis.

We conducted TANOVAs for MEPs, AEPs, and covariance maps within the components resulting from the microstate analysis, as outlined below. We conducted these TANOVAs on the covariance data after normalizing all data to the unit GFP. This normalization eliminated quantitative differences between the maps owing to scaling differences in the predictors (Habermann et al., 2018).

TCT and TANOVA analyses were computed in the MATLAB-based program Ragu (Koenig et al., 2011).

2.5.6. Testing of H1 (N100)

According to previous literature findings on auditory N100 attenuation for self-generated sounds, we expected an attenuated N100 for self-made sounds compared to that for beep-only. Additionally, we anticipated that the covariance map of probability, delay, and subjective agency rating with the AEP N100 would yield inverted maps compared with the N100. This is because an increasing probability and a decreasing delay for self-made sounds should produce a stronger attenuation and therefore show an inverted N100 on the covariance map. Similarly, concerning subjective agency rating, we anticipated an inverted covariance map for the N100 component. This expectation arose from the understanding that higher subjective ratings would indicate greater confidence in the experience of being the cause of the sounds.

To test the first assumption, we conducted a one-factorial repeated measures TANOVA across subjects comparing the sound types, beep-only and self-made sound, for the N100 mean AEP. To investigate the second assumption regarding whether the N100 AEP of the self-made sound was influenced by experimental manipulation and the subjective agency rating, we conducted across-subjects TCTs for the covariance maps: First, we performed within-subject covariance analyses with the predictors probability, delay, and subjective agency rating to extract the effect of these predictors on the single-trial N100 AEPs of the self-made sounds for each subject. We then computed across-subjects TCTs to investigate whether the scalp field maps representing the neurophysiological correlates of variations in the predictors were stable across subjects.

2.5.7. Testing of H2 (Perimotor Component)

The second hypothesis predicted that our experimental manipulations (delay and probability) and the subjective experience of agency would systematically influence perimotor evoked potentials. Similar to the procedure fo H1, we first performed within subject covariance analyses with the predictors probability, delay, and subjective agency rating to extract the effect of these predictors on the single-trial MEPs of the button presses. We when conducted a TCT to investigate whether the thereby obtained scalp field maps representing the neurophysiological correlates of variations in delay, probability, and subjective agency rating in the MEPs were consistent across subjects.

Finally, to determine whether our predictors were associated with different regions of the brain, we conducted a one-factorial, repeated measures TANOVAs across subjects of the covariance maps in the perimotor component, with the predictor type as a within-subject factor.

2.5.8. Testing of H3 (Random Sound)

Our third hypothesis predicted that experimental manipulations and subjective agency ratings would systematically influence the N100 AEP of the random sounds. Because we investigated the N100 of the self-made sounds, we focused on the same time window for random sounds. We conducted a TCT to test whether the correlates of the experimental manipulations were consistent across subjects in the N100 AEP of the random sounds.

Furthermore, we wanted to examine whether different brain regions were associated with delay, probability, and subjective agency judgment for random sounds compared with those for self-made sounds. Therefore, we conducted a two-factorial TANOVA of the covariance maps with the two within-subject factors of predictor type (delay, probability, and subjective agency rating) and sound type (random sounds and self-made sounds) for the N100 AEP.

2.5.9. Testing of H4 (Sense of agency and SPQ)

The fourth hypothesis predicted that schizotypal personality traits would be related to SoA. To investigate the neuronal correlates of subjects' SPQ-G scores on subjective agency ratings, we included the SPQ-G sum score as a between-subjects factor in the analysis of the ERP components, where the previous hypotheses provided substantial evidence of SoA effects. Thus, we conducted a two-factorial TANOVA with predictors (delay, probability, and subjective agency rating) as the within-subjects variable and the SPQ-G score as the between-subjects variable.

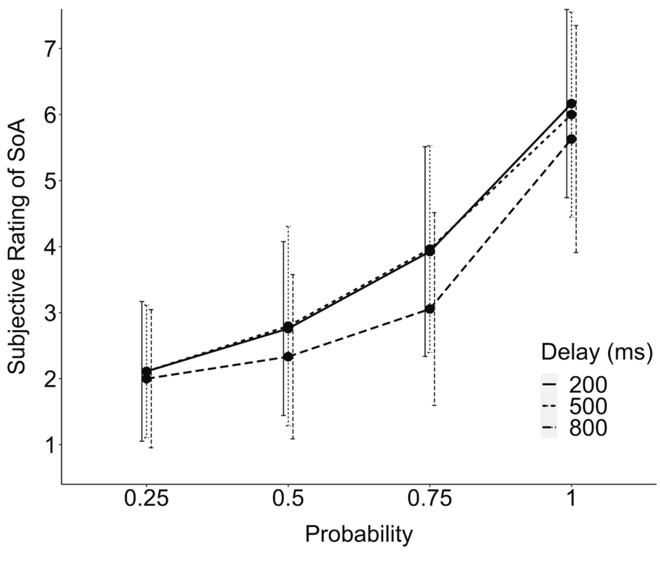

Fig. 2. *Subjective Sense of Agency Rating for the Different Experimental Manipulations. Note.* Subjective rating scale: 1 = *I do not agree at all* to 7 = *I fully agree*. Error bars show the standard deviation.

3. Results

3.1. Behavioral data

The SPQ-G scores ranged from 0 to 31 (*Mean* = 10.72, *Standard deviation* = 8.90, *Median* = 9.50, see also Fig S2 of the supplementary material). The linear mixed model that aimed to explain the variance in the subjective ratings of agency across blocks and subjects by systematic influences of the factors sound delay, sound probability and individual SPQ-G score revealed a significant effect of sound probability ($\beta = 5.97$, $SE = 0.82$, $t = 7.29$, $p < 0.001$, Cohen's d = 1.72). The fixed effects of delay, SPQ-G, and their interactions were not significant (all $p > 0.41$, all Cohen's ds < 0.2). The mean ratings as functions of probability and delay are shown in Fig. 2.

3.2. Segmentation of the components

The selected MEP microstate model (Fig. 3) consisted of three components and yielded an early microstate from −482 to −64 ms (premotor microstate), a second microstate from −64 to 64 ms (perimotor microstate), and a late microstate from 64 to 200 ms (postmotor microstate). These components were very similar to the two and four microstate models; these models only added or omitted components outside of the time periods of interest.

For the AEP, the selected microstate model (Fig. 4) included five microstates: an early pre-N100 microstate from 0 to 49 ms, a second microstate from 49 to 127 ms (N100 AEP), a third microstate from 127 to 281 ms (P200 AEP), a fourth microstate from 281 to 397 ms (early P300 AEP), and a late microstate from 397 to 500 ms (late P300 AEP). Alternative microstate models yielded similar results for the first four components.

3.3. H1: N100 confirmation

The configuration of the N100 AEP maps displayed central negativity and temporoparietal positivity for the self-made sounds and beep-only (Fig. 5). Significant differences between the two sound types ($p = 0.018$) were indicated by TANOVA. The t-map contrasting the self-made against random beep-evoked N100 showed a pattern of central positivity (t_{max} at Fz = 3.886) and temporoparietal negativity (t_{min} at TP7 = -3.664). These observations are jointly compatible with sources in the left and right auditory cortices (Näätänen & Picton, 1987) and indicate an attenuated N100 AEP, and thus assumingly less activity in the auditory cortices, for the self-made sound compared with that for the beep-only.

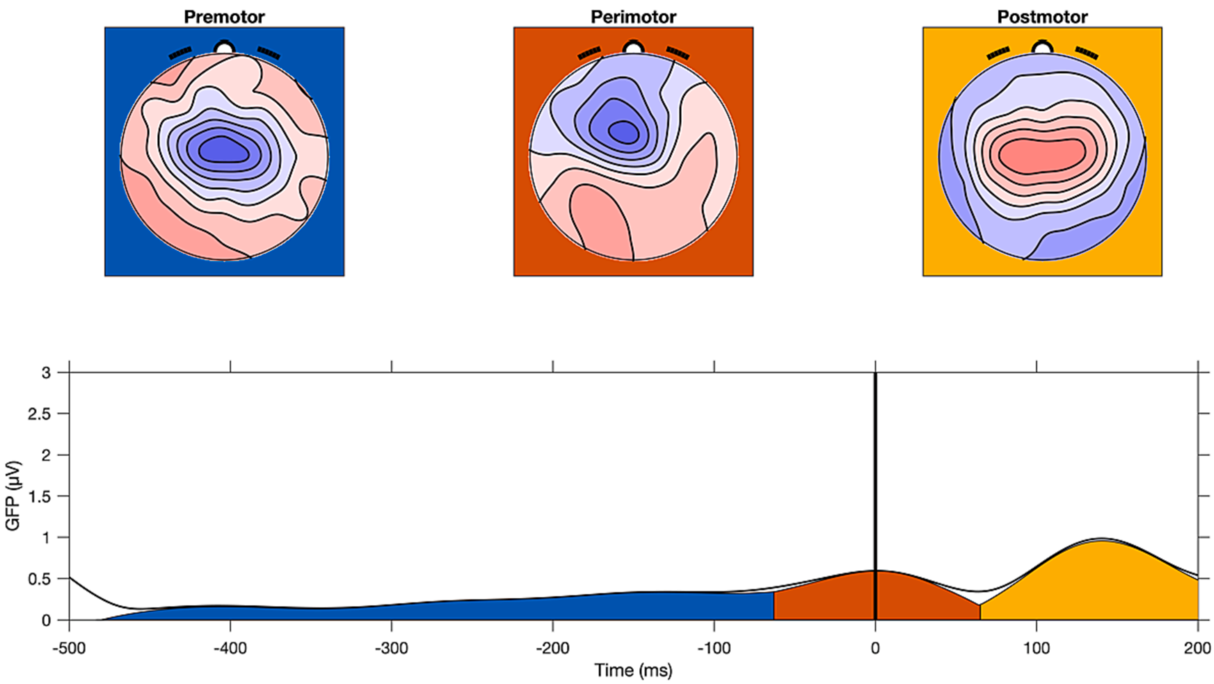

Fig. 3. *MEP Microstates. Note*. Below, the GFP (y-axis) for the time windows of the MEP microstates in ms (x-axis) is shown. Above, the MEP maps are shown for the three different time windows (blue: premotor from −482 to −64 ms; orange: perimotor from −64 to 64 ms; yellow: postmotor from 64 to 200 ms). The background color of the maps corresponds to the coloring of the time windows. MV: microvolts; GFP = Global Field Power; MEP = motor evoked potential; ms: milliseconds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

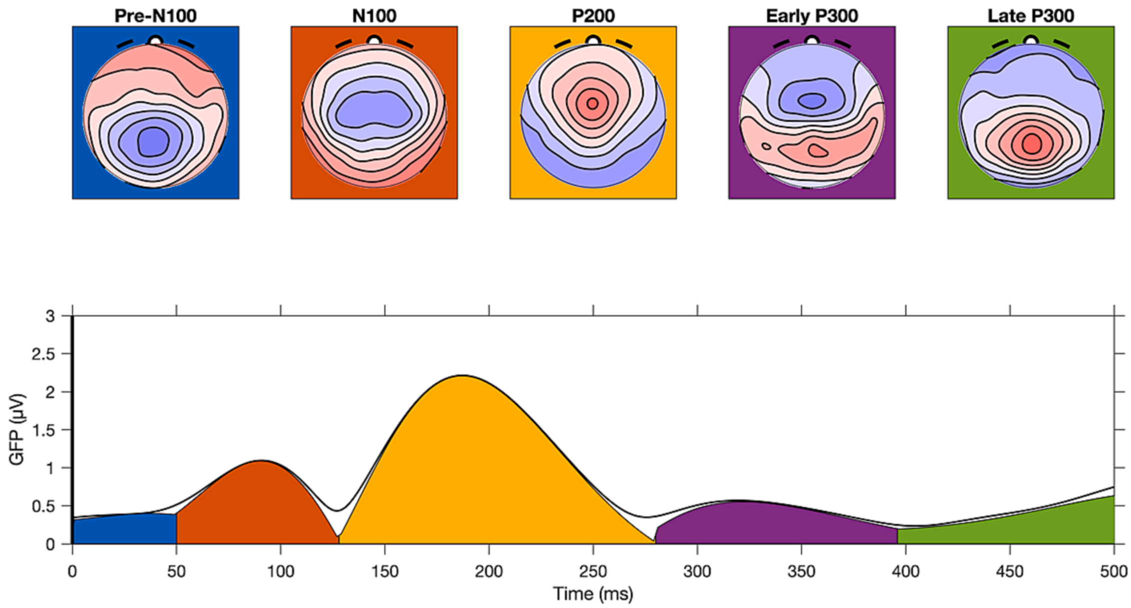

Fig. 4. *AEP Microstates. Note*. Below, the GFP (y-axis) for the time windows of the AEP microstates in ms (x-axis) is shown. Above, the AEP maps are shown for the five different time windows (blue: pre-N100 from 0 to 49 ms; orange: N100 from 49 to 127 ms; yellow: P200 from 127 to 281 ms; purple: early P300 from 281 to 397 ms; green: late P300 from 397 to 500 ms). The background color of the maps corresponds to the coloring of the time windows. MV: microvolts; AEP = auditory evoked potential; GFP = Global Field Power; ms: milliseconds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The TCT showed significant covariations in the AEP of the self-made sounds and every predictor (all $p < 0.001$). Maps with frontal positivity for rating covariance and frontocentral positivity for probability covariance indicated an inverted N100 as the corresponding predictor increased (Fig. 6). However, contrary to the effect obtained for increased probability and rating, for decreased delay the covariance map showed lateralized frontal negativity and temporoparietal positivity (Fig. 7).

To further explore whether the covariance maps of the predictors differed, we performed a TANOVA. The covariance maps of the three predictors differed significantly ($p = 0.00020$). To investigate this, pairwise TANOVAs were employed. As expected from Fig. 6, we found that the covariance map of the predictor delay differed from that obtained for probability ($p = 0.0004$) and for rating ($p = 0.0002$), whereas the latter two were not significantly different ($p = 0.0908$).

3.4. H2: Perimotor component

The TCT revealed a significant covariation between delay ($p = 0.0022$), probability ($p = 0.001$), and the perimotor component (Fig. 1). A marginal effect was observed for rating ($p = 0.067$). Maps for probability and rating indicated stronger frontal negativity and positivity in the temporal area with increasing values of predictors (Fig. 1) and were similar in configuration to the map of the perimotor microstate (Fig. 7). TANOVA yielded no significant differences between the covariance maps of the distinct predictors ($p = 0.3814$).

3.5. H3: Random sound

The N100 of the random sounds showed a map configuration of central negativity and temporoparietal positivity (Fig. 8).

Supporting our assumption that the random sounds N100 were affected by our experimental manipulations, TCT revealed significant covariations in the N100 AEP with delay ($p = 0.002$) and probability ($p = 0.0152$) (Fig. 9). For the subjective agency rating, the TCT also yielded a significant covariation with the N100 AEP of random sounds ($p = 0.0408$) (Fig. 9).

To investigate whether different brain regions were connected to the three predictors for self-made sounds compared with those for random sounds, we conducted a two-factorial TANOVA of the covariance maps, with sound type and predictor as within-subject factors. The TANOVA yielded a significant main effect of predictor ($p = 0.0002$) and a significant interaction between sound type and predictor ($p = 0.0094$). The main effect of the sound type ($p = 0.185$) was not significant. To further investigate the significant interaction effect of the sound type and predictor, paired TANOVAs were performed. A TANOVA comparing the covariance maps of delay obtained in the self-made and random sounds yielded no significant effect ($p = 0.2216$). A comparison of the probability covariations in the same two sound types showed a marginally significant difference ($p = 0.0542$), with a pattern of occipital positivity ($t_{max} = 3.875$ at O1) and left hemispheric frontal negativity ($t_{min} = -3.160$ at F7) (Fig. 4). Comparing the covariance maps of the two sound types with the subjective agency rating, TANOVA revealed a significant difference ($p = 0.0274$), with a t-map showing parietal

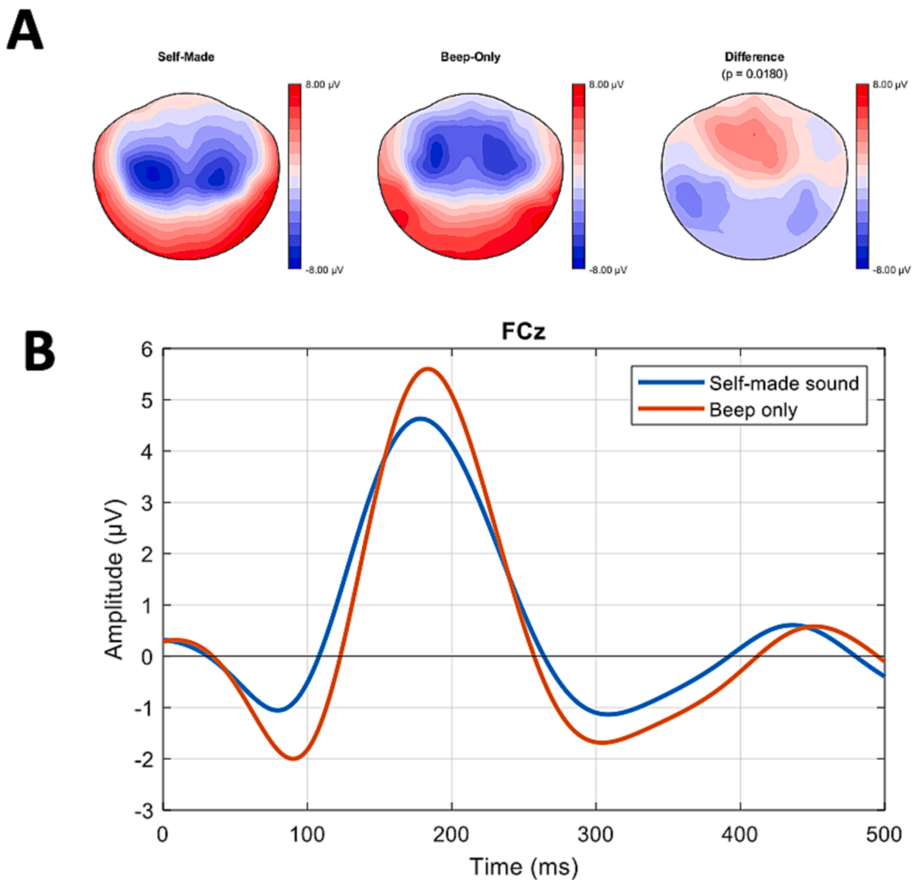

Fig. 5. *N100 ERP Mean Maps and Difference Map. Note.* A: Mean maps of the N100 of the self-made sound and beep-only and the difference map (Diff). The maps are shown with contour lines in steps of 0.5 µV. The p-value indicates the significance of the difference map. ERP = event related potential. B: Traces of the same ERPs at channel FCz, The suppression of the N100 in the self-made condition is clearly visible. µV: microvolts; ms: milliseconds. The experimental condition explained 16.6 % of the individual variance between condition.

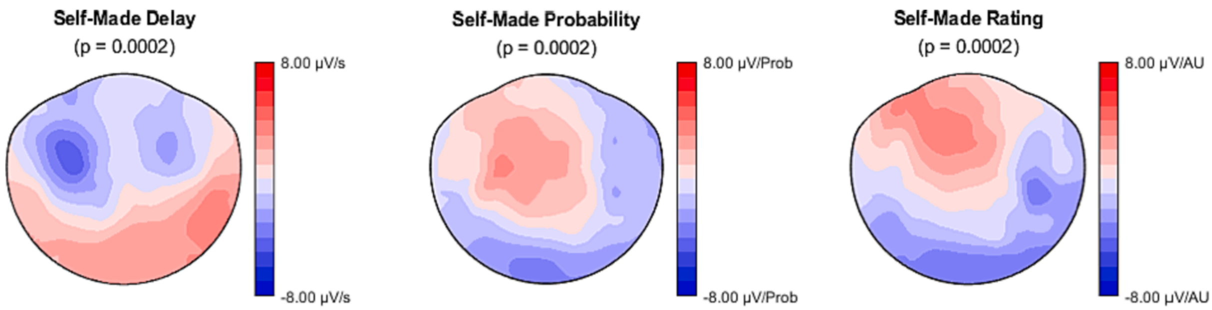

Fig. 6. *N100 Covariance Sound t-Maps. Note.* Covariance maps of the N100 of the self-made sound with the three predictors. The maps are shown as electrodewise single-sample t-values with contour lines in steps of 1 t. P-values indicate the significance of the TCT. TCT = Topographic Consistency Test. The grand mean covariance map of the N100 explained 42.5 % (delay predictor), 40.7 % (probability predictor), and 48.6 % (Rating predictor) of the variance of the individual covariance maps of the self-made sounds. µV: microvolts; AU: arbitrary units; p: p-value; prob: probability; s: seconds.

and occipital positivity (t_{max} = 3.239 at PO10) and left hemispheric frontal negativity (t_{min} = -4.333 at AF7) (Fig. 10).

3.6. H4: Sense of agency and SPQ-G

The criterion for further investigation of the relationship between the SPQ-G and SoA was that the effect of the subjective agency

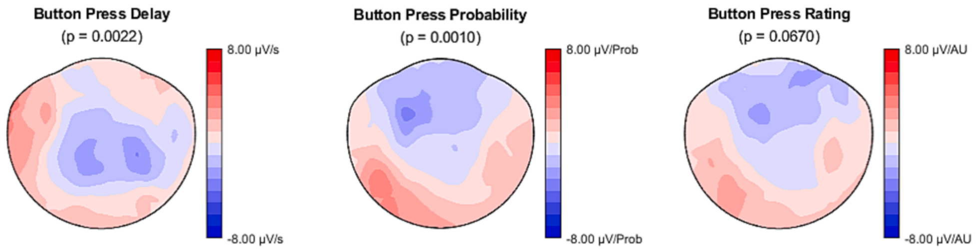

Fig. 7. *Perimotor Covariance t-Maps. Note.* Covariance maps of the perimotor component with the three predictors. The maps are shown as electrodewise single-sample t-values with contour lines in steps of 1 t. P-values indicate the significance of the TCT. TCT = Topographic Consistency Test. The grand mean covariance map of the perimotor component explained 30.8 % (delay predictor), 31.9 % (probability predictor), and 28.6 % (Rating predictor) of the variance of the individual covariance maps of the motor-evoked potential. µV: microvolts; AU: arbitrary units; p: p-value; prob: probability; s: seconds.

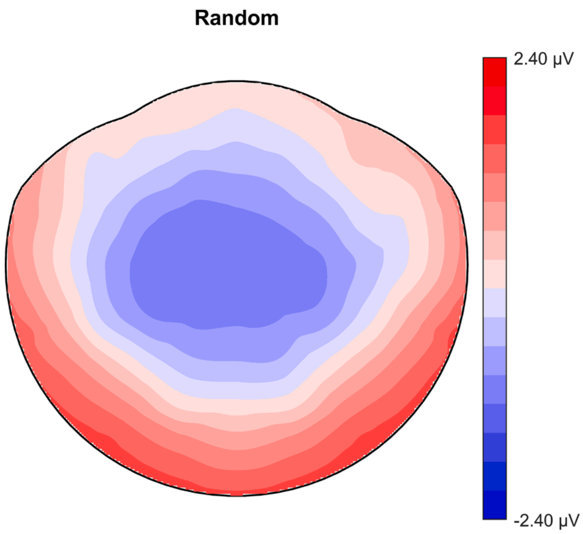

Fig. 8. *N100 ERP Sound Mean Map. Note.* Mean map of the N100 for random sounds. The map is shown as electrodewise single-sample t-values with contour lines in steps of 0.3 µV. ERP = event related potential. µV: microvolts.

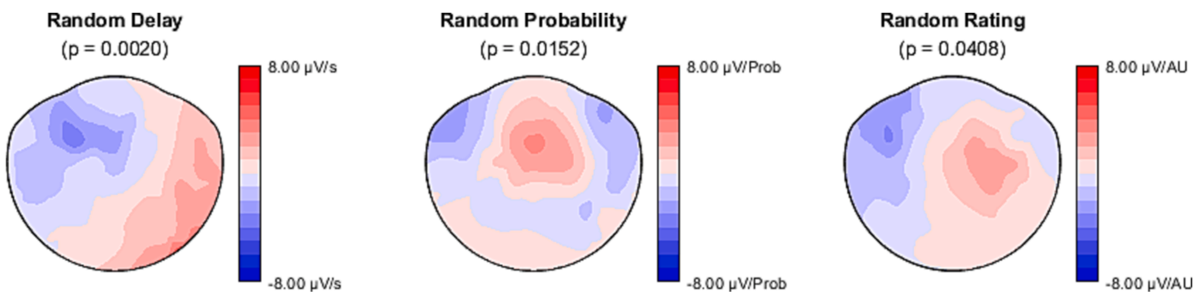

Fig. 9. *N100 Covariance Sound t-Maps. Note.* Covariance maps of the N100 of random sounds with the three predictors. The maps are shown as electrodewise single-sample t-values with contour lines in steps of 1 t. P-values indicate the significance of the TCT. TCT = Topographic Consistency Test. The grand mean covariance map of the N100 explained 32.9 % (delay predictor), 29.4 % (probability predictor), and 30 % (Rating predictor) of the variance of the individual covariance maps of the random sounds. µV: microvolts; AU: arbitrary units; p: p-value; prob: probability; s: seconds.

rating or probability should be significant in the relevant components. As mentioned in the section concerning the perimotor component, the TCT showed significant covariation between probability and delay with the MEP of the perimotor microstate. For the subjective agency rating, covariation with the MEP of this microstate was marginally significant. Therefore, we further explored the relationship between the SPQ-G and SoA in this perimotor component using covariance maps of the three predictors as dependent variables. The two-factorial TANOVA showed no significant main effect of predictor ($p = 0.3722$) and SPQ-G score ($p = 0.2366$) but a

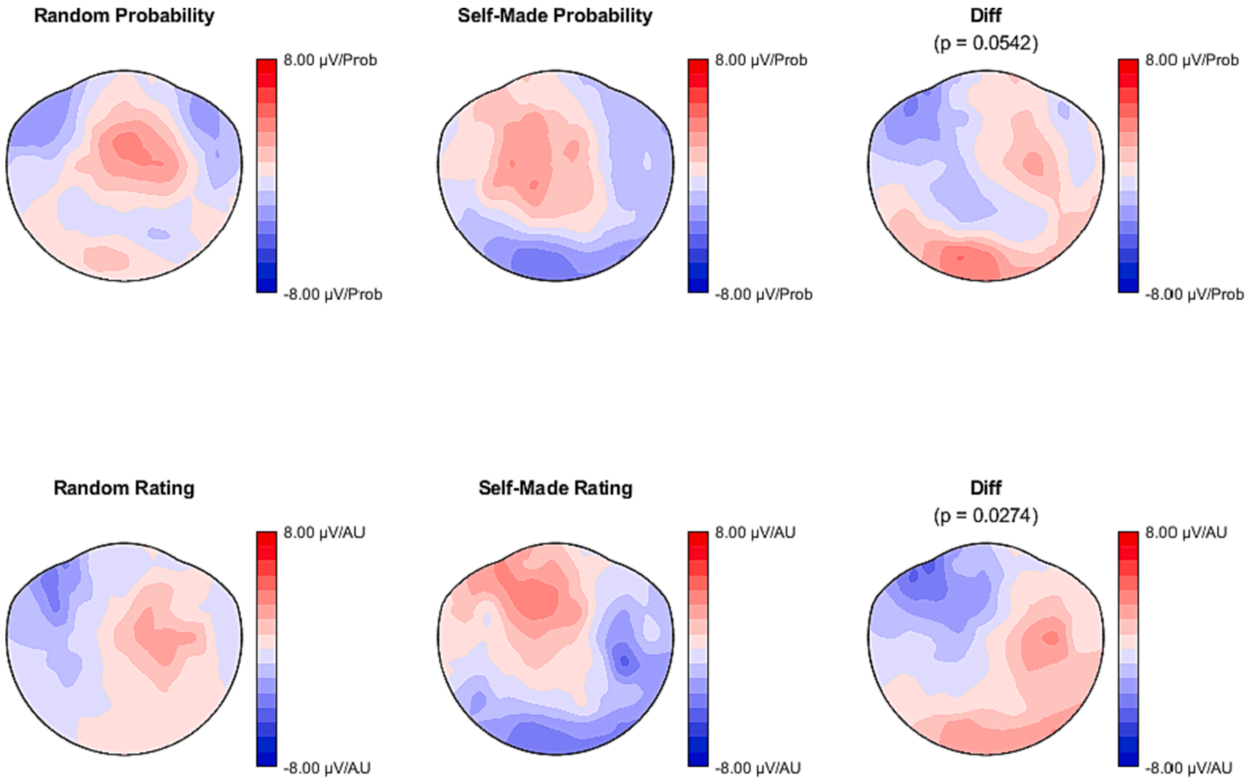

Fig. 10. *N100 Covariance Sound t-Maps and Difference Maps. Note.* Covariance maps (left and center) and difference maps (right) of the N100 of the self-made and random sounds with the two predictors probability and rating. The maps are shown as electrodewise single-sample t-values with contour lines in steps of 1 t. P-values indicate the significance of the difference maps. In the comparison of the probability covariance maps between random and self-made sounds (upper row), the factor sound type explained 10.48 % of the variance. In the comparison of the rating covariance maps between random and self-made sounds (lower row), the factor sound type explained 12.30 % of the variance. µV: microvolts; AU: arbitrary units; Diff = difference map; p: p-value.

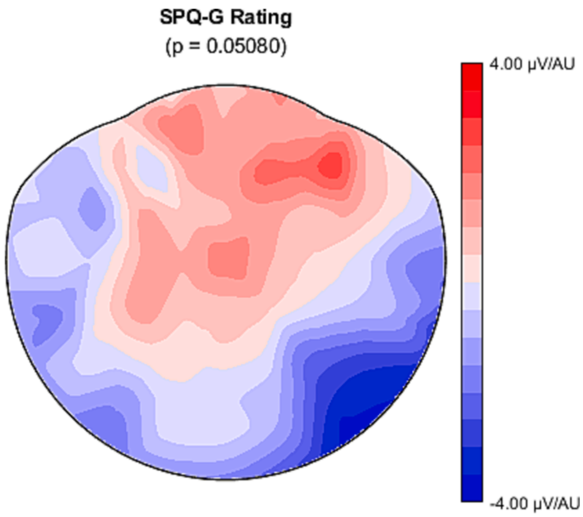

Fig. 11. *Perimotor Covariance SPQ-G Rating t-Map. Note.* Covariance map of the perimotor component with rating and SPQ-G. The map is shown as electrodewise single-sample t-values with contour lines in steps of 0.5 t. P-values indicate the significance of the TCT. The SQP-G score explained 10.24 % of the variance of the individual perimotor ERP component. µV: microvolts; AU: arbitrary units; p: p-value; TCT = Topographic Consistency Test.

nearly significant effect for the interaction between SPQ-G score and predictor ($p = 0.0512$). To further examine the effect of the SPQ-G on the covariation of each predictor with the MEP of the perimotor component, we performed TANOVAs for each predictor using the SPQ-G as a between-subjects variable. There was no significant main effect of the SPQ-G score in the TANOVA, including delay ($p = 0.66840$), a marginal main effect with probability ($p = 0.0924$), and a nearly significant main effect in the TANOVA including rating ($p = 0.0508$) (Fig. 11). The covariance map of the perimotor component with rating and SPQ-G obtained after the reversion of its polarity was similar to the perimotor ERP microstate topography (Fig. 3) and the topography of the perimotor covariance maps of ratings (Fig. 7) but lacked lateralization. TANOVA with sound type, predictor, and SPQ-G score of the N100 covariance maps yielded no significant effects (all $p > 0.17$) that included the SPQ-G score. Therefore, no further post hoc tests were performed.

4. Discussion

We investigated whether there are aspects of SoA that go beyond the comparator model and explored how these aspects can be measured using electrophysiological methods. Our findings confirmed previous evidence supporting the comparator model but also provided evidence for neurobiological representations of the SoA that are challenging to elucidate using the comparator model. Specifically, we identified an early motor-based neuronal correlate of pre-reflective SoA and discovered that schizotypal personality traits affect this correlation. Furthermore, our study showed that neural processing of environmental stimuli can be modulated by manipulating the SoA.

Regarding the confirmatory aspect of our findings, we first observed that the behavioral data provided evidence supporting the successful implementation of our experimental manipulations. Explicit agency rating could be predicted based on the probability of self-generated stimuli. The delay in the self-made sound and the schizotypal personality traits of the participants did not predict explicit agency rating. Regarding delay, this is in line with the conclusion of a recent review indicating that “delay does not impair the perception of causal relations between one’s action and feedback” (Wen, 2019, p. 6). Therefore, by varying the probability, we were able to systematically influence the authorship experience. Contrary to our hypothesis 4, there was no significant association between the SPQ-R scores and the subjects’ agency ratings. While negative findings typically allow for more than one logically possible explanation, we speculate here that there may have been other and large sources of variance in the subjects’ mean ratings of agency that obscured such a putative effect.

In the first step of our analysis of the neurophysiological data, we aimed to replicate N100 suppression for self-generated sensory stimuli. Our results successfully demonstrated a reduction in the N100 component of self-generated sounds compared with that of randomly occurring sounds. These findings are in line with those of previous research in the motor-auditory field by Baess et al., (2008,2011) and Timm et al. (2014). Therefore, our findings provide evidence for the forward model (Frith et al., 2000; Wolpert, 1997), showing that the predictions generated by the forward model when acting lead to a reduction in the neuronal response through the predicted self-generated sound.

Similarly, the relationship between N100 and the probability of self-generated sounds indicated that a more predictable situation was associated with a stronger attenuation of self-generated sounds. In other words, the covariation map of probability yielded an inverted N100, similar to the difference map, indicating a sensory attenuation effect. As expected, this was reflected in the electrophysiological correlate of subjective experience. Specifically, a similar map for the covariation of N100 with subjective agency ratings showed an attenuated N100 of self-generated sounds with an increasing subjective experience of agency. This suggests that the N100 suppression effect is correlated with explicit SoA. This is contrary to the existing findings of Kühn et al. (2011), which indicated that agency judgment was not reflected by N100.

One possible explanation for these inconsistent findings could be different experimental designs. In our study, we asked participants to make ratings on their explicit SoA, while we systematically modulated a context that strongly affected their expectations of agency. In contrast, the participants in Kühn et al. (2011) made agency judgments after each button press for ambiguous stimuli presented in an ambiguous but constant context. This may have caused the participants (contrary to our case) to respond according to their judgment rather than their feeling of agency.

Another difference that could have led to the difference in the findings could be that Kühn et al. (2011) had a setup in which all button presses were followed by a tone, and no tones occurred without the button press. Thus, their data were insensitive to the motor contribution to the explicit SoA. Our findings showed a similarity between the difference map of self-made and beep-only and the covariation map of the N100 AEP with subjective agency ratings. Based on these observations, we believe that motor action contributed to explicit SoA, as assessed in our experimental setup. In simpler terms, if we assume that the only difference between the beep-only and self-made sounds is motor prediction and action, and the N100 attenuation reflects this, our covariance mapping results strongly suggest a contribution of motor preparation to the later explicit SoA.

Although we found an effect of delay in the N100, the spatial distribution of this effect was different from the distribution of the other covariates, and it did not resemble the suppression of the N100 observed when comparing self-made sound with beep-only N100 maps. In addition, the delay did not affect SoA in the behavioral data; therefore, we assumed that the identified representation of the delay in N100 was unrelated to SoA. Therefore, we do not discuss this finding further.

After confirming the previous findings, we turn to the core topics of our study. We assumed that the SoA emerges before and during the action, and should thus be apparent in the perimotor microstate component. Our results confirmed that subjective ratings of the SoA were associated with neuronal activity in the perimotor component. This finding is important because the assumptions of the comparator model suggest that the experience of agency arises from a comparison between the predicted state, involving predictions about consequences and changes to the motor system, and the actual state (Moore, 2016).

In other words, the comparator model suggests an SoA that emerges post hoc. In contrast, our findings showed that an a priori neuronal correlate of explicit SoA was present in the EEG before and during motor activity. Our data also suggest that this effect can be considered as an increase in RP, since the obtained covariance maps closely resemble the perimotor ERP microstate topography. The current finding is consistent with evidence from previous studies on motor-auditory and visuomotor processes, such as the work by Ford et al. (2014) and Vercillo et al. (2018). These studies demonstrated greater (lateralized) RP preceding actions that resulted in feedback than before actions that were not followed by any stimuli. This led us to draw the following several conclusions. First, the pre-reflective SoA elicited in our paradigm is represented by the perimotor-evoked potential, indicating that it is not confined to the processing of the stimulus, as outlined by Synofzik et al. (2008). Second, the explicit rating of agency, as collected in our study, must have been related to pre-reflective SoA. This finding is consistent with the two-step approach explained by Synofzik et al. (2008) and the phenomenological perspective of the self. From this perspective, the pre-reflective SoA is a basic component of the self that contributes to the reflective SoA (Gallagher, 2000; Gallagher & Zahavi, 2008). Third, our findings support the notion that the functional scope of the RP extends beyond motor planning and preparation. It appears to be sensitive to the participant's expectations regarding the outcomes or consequences of the motor act (Hughes & Waszak, 2011; for a review of recent literature on the RP see Schurger et al., 2021). Lastly, our manipulation of the SoA by varying the probability of eliciting tones was represented in the perimotor component. Our interpretation of this finding was that the fluctuating expectancy of the self-made sound influenced the subjective experience of the SoA even before the action took place, resulting in a more or less distorted SoA.

In addition, we investigated the experience of agency in externally generated events that were not predictable to participants. Thus, we were interested in understanding how the manipulation of delay, probability, and subjective SoA influenced the sensory processing of random sounds. Our results demonstrated that alterations in expectations related to SoA were reflected in the neural processing of these random stimuli. The observed inverted topography of the N100, resulting from the covariation of random sound and probability, indicated that there was greater sensory attenuation of random sounds when the probability of self-made sounds was high, and when participants reported more agency overall. Therefore, we concluded that the attenuation of the N100 was not selective for self-generated sounds when the stimuli were more predictable based on button presses. In addition to previous results of Baess et al. (2011), which showed evidence for the selective attenuation of self-made sounds compared to computer-generated sounds occurring under the same experimental conditions, our results suggest that the attenuation of random and self-made sounds was dependent on the context. This was supported by the observation that the topographies of the contrast between the covariance maps of the self-made and random sounds were rather orthogonal to the N100 topography (Fig. 4). Moreover, the covariance maps of self-made and random sounds were consistently different, indicating that they originated from distinct neuronal sources. These findings are in line with the comparator model, which assumes that self-generated and therefore predictable stimuli are processed differently from unpredictable stimuli from the environment (Haggard, 2017). However, contrary to the comparator model, we showed sensory attenuation for random sounds, which suggests that no exact matching from the prediction and sensory feedback is necessary to attenuate sensory stimuli.

For the delay manipulation, no effect on sensory attenuation occurred, as the topography of the covariance map with delay (Fig. 3) was very different from that of an inverted N100 map. We suggest that this occurred because the delay had no detectable effect on the occurrence of random sounds and thus did not affect the attenuation of the N100 of random sounds. Overall, the processing of random events should be investigated in more detail when studying SoA.

Finally, we hypothesized that SoA would be related to schizotypal personality traits. Our results showed no effect of SPQ-G score on N100 AEP. This finding is in line with the results of a previous study by Oestreich et al. (2015), which demonstrated no difference in N100 attenuation between individuals with high or low schizotypal personality trait scores when motor-evoked tones were delayed by 50 ms or more.

Our findings revealed that higher SPQ-G scores impacted the covariance maps of the ratings within the perimotor ERP microstate. Interestingly, this effect exhibited an opposite pattern compared to that of the topography of the perimotor ERP microstate itself and the topography of the covariance of this microstate ERP with rating.

We interpret this finding as a decrease in the effect of agency rating on the evoked potential in people with high SPQ-G scores. In other words, this effect, which can be interpreted as a positive correlation between RP and SoA, suggests that the representation of SoA in RP is less pronounced in individuals with high SPQ-G scores. Considering that SoA is an a priori experience and an important component of the minimal self (Gallagher, 2000, 2012), we argue that this a priori and pre-reflective sense contributes less to the experience of authorship in people with higher schizotypal personality traits. Following the idea proposed by Ford et al. (2014) regarding impaired efference copy mechanisms in individuals with disorders within the schizophrenia spectrum, we conclude that individuals with higher levels of schizotypal traits exhibit reduced reliance on the efference copy in their explicit sense of agency.

Our study has some limitations. First, the sample size is small, which may affect the generalizability of our results to larger populations. At the same time, our results showed internal consistency. The covariance maps of rating and probability closely resembled the (independently obtained) contrast between self-caused sounds and the beep-only ERP (Figs. 5 and 6), and the within-subject effects of probability and rating in the perimotor ERP component (Fig. 7) confirmed the between-subject effect of the SPQ-G in the same component (Fig. 11). Therefore, it is both important and promising to validate our findings by conducting further investigations with larger sample sizes. We recommend implementing a preselection process to include individuals with either high or low schizotypal personality trait scores. This approach allows for the exploration of SoA at both extremes of this dimensionally distributed personality trait. Another limitation is the relatively young mean age of the sample. This could limit the generalizability of our findings to other age groups, as brain maturation processes may be incomplete in younger participants. However, it is important to note that schizophrenia typically occurs within this age range and that clinical EEG studies in this field are often carried out with younger samples. Therefore, the relatively young age of our participants may have enabled the comparability of our results and strengthened the relevance of our findings.

When it comes to motor-evoked potentials, handedness is an important confounder. Our already small sample included 3 left-handers, which makes it problematic to systematically assess or exclude the effects of handedness. Future studies should, therefore, aim to design their study in a way that the effect of handedness can be systematically assessed.

Another limitation of our study is the fact that our analyses have not taken into account that the subjects were likely to update their expectancies within each block. To account for this, one would have to introduce the within-block trial number and/or beep number as an additional factor to our analysis. This would have entailed an even more complex set of analyses and results than what we already had. In conjunction with the limited sample size and the novelty already introduced by our, to some degree, unconventional analysis strategies, we thought this would overload the paper and refrained from conducting such further analyses.

5. Conclusions

In conclusion, our findings suggest that the brain processing before and during an action contributes to the experience of agency. This does not put into question the important and empirically well-supported feedback mechanisms contained in the comparator model but suggests that relying solely on post hoc matching of predictions and actual states may not be sufficient to fully capture SoA. Furthermore, our study highlights the significance of expectancy and contextual factors in the processing of random events, which offers a more comprehensive understanding of the complex nature of the authorship experience.Our findings suggest the potential use of schizotypal personality traits to investigate divergent agency experiences in the general population. Finally, we propose that our experimental design will yield important additional findings on the complex neurobiology of the SoA when applied to a population of patients on the schizophrenia spectrum.

6. Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Nena Luzi: Conceptualization, Data curation, Writing-original draft, Visualization, Investigation, Formal Analysis, Writing-review & editing, Visualization. **Maria Chiara Piani:** Writing-original draft, Investigation, Writing-review & editing, Visualization **Daniela Hubl:** Writing-original draft, Supervision **Thomas Koenig:** Conceptualization, Writing-review & editing, Visualization, Validation, Formal Analysis, Methodology, Supervision

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2024.103667.

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