The evolving sense of agency: Context recency and quality modulate the interaction between prospective and retrospective processes

Simone Di Plinio^{1*}, Simone Arnò², Mauro Gianni Perrucci^{1,3},
Sjoerd J.H. Ebisch^{1,3}

¹ Department of Neuroscience Imaging and Clinical Sciences, G.
D'Annunzio University of Chieti-Pescara, Chieti 66100, Italy;

² Department of Psychological Sciences, G d'Annunzio University of
Chieti-Pescara, Chieti, Italy;

³ Institute for Advanced Biomedical Technologies (ITAB), G
d'Annunzio University of Chieti-Pescara, Chieti, Italy;

*** Corresponding author.** Address: Department of Neuroscience Imaging
and Clinical Sciences, G. d'Annunzio University of Chieti-Pescara,
Chieti 66100, Italy. E-mail: simone.diplinio@unich.it

Conflict of Interest: The authors declare no competing financial
interests.

Running Head: Interaction among agency subprocesses

Keywords: Intentional binding; Sense of Agency; Psychosis;
Sensorimotor learning; Implicit learning; Perception.

Funding: This work was supported by the BIAL Foundation grant number
195/16 to SE, and by the "Departments of Excellence 2018-2022"
initiative of the Italian Ministry of Education, Research, and
University for the Department of Neuroscience, Imaging and Clinical
Sciences (DNISC) of the University of Chieti-Pescara.

ABSTRACT

Humans acquire a sense of agency through their interactions with the world and their sensory consequences. Previous studies have highlighted stable agency-related phenomena like intentional binding, which depend on both prospective, context-dependent and retrospective, outcome-dependent processes. In the current study, we investigated the interaction between prospective and retrospective processes underlying the adaptation of an ongoing sense of agency. The results showed that prospective intentional binding developed during a temporal window of up to 20 prior events were independent of the nature of the ongoing event. By contrast, the characteristics of the ongoing event retrospectively influenced prospective intentional binding developed during a temporal window narrower than 6 prior events. These findings characterize the interaction between prospective and retrospective mechanisms as a fundamental process to continuously update the sense of agency through sensorimotor learning. High psychosis-like experience traits weakened this interaction, suggesting that reduced adaption to the context contribute to altered self-experience.

1. INTRODUCTION

The sense of agency is the feeling of controlling the initiation and execution of our actions and of assimilating their consequences thereof. There is a consensus that humans acquire a sense of agency through their interactions with the environment and particularly through the sensory feedback of performed actions. The relevance of understanding the many facets of the sense of agency is underlined by both its importance for healthy development (Synofzik et al., 2013; Haggard, 2017; Bandura, 2018) and its disruption in psychopathology (Hauser et al., 2011; Moore & Fletcher, 2012; Moore, 2016).

A commonly used approach to investigating the sense of agency and its alterations is the exposure of participants to experimental conditions that differ in the predictability of sensory feedback (Haggard et al., 2002), in the temporal proximity between actions and consequences (van Kemenade et al., 2018; Wen, 2019), or in the subjective degree of control induced in the participant (Kumar & Srinivasan, 2013). During the procedure, implicit or explicit ratings of agency are collected in a series of events and are often averaged within specific conditions (Haggard, 2017; Imaizumi & Tanno, 2019).

Some implicit ratings of agency-related perceptual phenomena have been described as stable, unbiased, and replicable measures of the sense of agency. For instance, intentional binding (Haggard et al., 2002; Voss et al., 2010; Berberian et al., 2012; Bohrani et al., 2017) is the subjective shift of the perceived timing of an action toward its consequence, or vice versa. Importantly, intentional binding effects can indicate a prospective or retrospective component of the sense of agency. A prospective component is based on a contextual and probabilistic event coding and is usually indicated by increased intentional binding in a context of high probability of action feedback, compared to a context of low probability. By contrast, a retrospective sense of agency concerns outcome-dependent, a posteriori inferences about the action feedback (Moore & Haggard, 2008; Synofzik et al., 2008, 2013).

Previous findings suggest that the sense of agency has a fundamental flexibility that conceivably arises from the online

adaptation of sensorimotor predictions during ongoing behavior (Clark, 2013). By mediating the development of action awareness, implicit sensorimotor learning may be a fundamental process in establishing the sense of agency (McDougle et al., 2016; Kim et al., 2019). Implicit learning is an endogenous process involved in generating and updating sensorimotor predictions in the brain (Friston & Kiebel, 2009; Wolpert et al., 2011; Legaspi & Toyoizumi, 2019; Di Plinio, Perrucci, & Ebisch, submitted) that affects behavioral temporal estimates (Taylor et al., 2014; Stark-Inbar et al., 2017). Therefore, implicit learning plausibly supports a continuous, trial-after-trial update of the sense of agency. Given that the context-based (prospective) sense of agency is based on the implicit learning of the consistency of the outcome-based (retrospective) element, we argue that prospective and retrospective mechanisms of the sense of agency are not independent; we propose that they may interact to continuously update the context generated by the quality of the sensory action outcome. However, the way in which prospective and retrospective mechanisms interact to continuously update the ongoing sense of agency is still poorly understood.

Especially regarding the prospective sense of agency, experimental paradigms typically assume that a given context is developed by the agent within a given run or block of sensorimotor events. However, this assumption depends on some critical premises. The first premise is *within-run homogeneity*: a run-based approach presumes that events within a given run are homogeneous. To the contrary, studies have reported within-run inhomogeneities (Moore et al., 2011; Moore et al., 2012; Sidarus et al., 2017), suggesting that contexts of increased versus decreased agency can alternate within the same run. Furthermore, although prospective and retrospective sense of agency are both based on the probability of the action outcomes, previous studies have typically distinguished prospective and retrospective sense of agency components without considering their interaction. However, outcomes could either confirm or contradict the agency context defined by prior events, possibly leading to conflicts between the prospective and retrospective components. Such conflicts could constitute relevant information which flexibly update a possibly changing context. Another premise is that there are *no cross-run*

interactions. This means that events in previous runs are presumed not to affect events in subsequent runs. This is highly improbable, because the perception of outcomes relies on both structural and contextual short-term expectations (Desantis et al., 2016; Dogge et al., 2019). Finally, the cross-participant pseudo-randomization of the run order is thought to avoid the introduction of run-order biases, while effects due to run order could provide additional information. Thus, it is reasonable to expect that critical insights into the constitution of the sense of agency can be achieved by investigating the prospective and retrospective sense of agency as interacting components within a context that is continuously updated through implicit sensorimotor learning.

The present study addressed several questions related to these issues. For example, are retrospective mechanisms based on single trial information, or are they influenced by the context? Similarly, are prospective-contextual mechanisms stable regardless of the nature of the ongoing action event, or do they also depend on the actual action outcome? How many events are necessary to establish a given context of a prospective sense of agency? We further explored the clinical relevance of the interaction between the prospective and retrospective sense of agency components. Because clinical symptoms of psychosis are correlated with an impaired adaptation to ongoing behavior (Frith et al., 2000; Blakemore et al., 2002; Ford & Mathalon, 2005; Moore & Fletcher, 2012; Martinelli et al., 2017; Bansal et al., 2019), we investigated how psychosis-relevant personality traits interact with the embodiment of a dynamic sense of agency. Considering previous literature on the association between uncertainty (or ambiguity) and psychosis (Linney et al., 1998; Van Dael et al., 2006; Garety et al., 2011), we hypothesized that there could be an interaction between the prospective and retrospective components which may create ambiguous situations of "conflict" between the expected and actual action outcomes and that this interaction may be relevant for psychosis-relevant traits.

To clarify these questions, and expanding on previous studies, the present study analyzed prospective and retrospective intentional binding effects by considering the entirety of the experiment as a

unique, subjective sequence of events in which the context is constantly updated. This approach was intended to avoid the biases of within-run inhomogeneity and cross-run interactions. We also tested whether intentional binding may change depending on how long a given context is assumed to last (e.g., a few trials vs. many trials). Thus, we investigated the effect of the context at multiple temporal scales. A relatively large number of participants was used to achieve high statistical power on a trial-based approach.

We hypothesized that the interaction between the prospective and retrospective sense of agency could be affected by the number of events considered to form a context. For example, more recent and earlier trials could reflect a "narrow context" and an "extended context," respectively. Whereas previous studies have shown that a context with a high probability of receiving sensory feedback increases the sense of agency, we expected that the percentage of feedback trials within narrow and extended contexts would differently influence the sense of agency. Individual differences in personality traits were investigated starting from the belief that increased psychosis-like experiences may affect individuals' adaptation to the ongoing behavior. Consequently, this aberrant adaptation may perturb the sense of agency measured by intentional binding, specifically when action outcomes conflict with context-based expectancies.

2. MATERIALS and METHODS

2.1. Participants

The overall sample of this study consisted of 101 non-clinical, healthy Italian adults (48 males and 53 females; age 23 ± 3). None of the participants had ever suffered from any psychiatric or neurological disorder. All the participants in the study had a normal or corrected-to-normal vision and gave written informed consent before taking part in the study. All the 101 participants completed the psychometric questionnaires included in the study, while a subset of 61 participants (29 males and 32 females; age 23 ± 3) was included for the sense of agency task (these include the 20 participants of the positive-control group in Di Plinio et al., 2019a and the 39

participants of the fMRI experiment in Di Plinio, Perrucci, and Ebisch, submitted). A relatively high number of participants was chosen for the study since we wanted to overcome biases related to the pseudo-randomization of runs and to perform trial-based analyses. Since the remaining 40 subjects performed a different version of the sense of agency task (as described in Di Plinio et al. 2019a), these 40 subjects were only used for the factor analysis on psychometric questionnaires.

2.2. Psychometric questionnaires

In a way analogous to a previous study (Di Plinio et al., 2019a), we investigated the relation between the sense of agency and personality traits with a focus on factors related to psychotic disorders (Asai et al., 2008; Jeannerod, 2009; Asai et al., 2011; Gallagher & Trigg, 2016). The following questionnaires were administered to the overall cohort (N = 101).

The Big Five Questionnaire (BFQ, Caprara et al., 1993), which follows the five-factor model (Costa & McCrae, 1985) was administered to participants. In the BFQ, the five personality dimensions are defined through sixty items rated from 1 to 5: neuroticism (12 items, $\alpha = 0.85$), extraversion (12 items, $\alpha = 0.61$), conscientiousness (12 items, $\alpha = 0.79$), agreeableness (12 items, $\alpha = 0.77$), and openness to experience (12 items, $\alpha = 0.73$).

The Intolerance of Uncertainty Scale (IUS-12, Carleton et al., 2007) was employed to assess the tolerance of uncertain situations. It consists of 12 items rated on a 5-points scale, for which two subscales are identified: inhibitory uncertainty (7 items, $\alpha = 0.73$) and prospective uncertainty (5 items, $\alpha = 0.81$).

The Community Assessment of Psychic Experience (CAPE, Konings et al., 2006) was used to assess the presence of psychosis-like in the general population through its three subscales: positive symptoms (20 items, $\alpha = 0.79$), negative symptoms (14 items, $\alpha = 0.82$), and depressive symptoms (8 items, $\alpha = 0.74$).

The Schizotypal Personality Questionnaire (SPQ, Raine, 1991; Fossati et al., 2003) consists of 74 questions to which the participants may answer "yes" (=1) or "no" (=0). The three subscales, which are made up by the sum of positive answers, are: cognitive-perceptual (25 items, $\alpha = 0.84$), interpersonal (33 items, $\alpha = 0.85$), and disorganized (16 items, $\alpha = 0.86$).

Finally, the State-Trait Anxiety Inventory (STAI2, Spielberger et al., 1983) is a 20-items scale. The participants are asked to rate each item from one to four. The final score is obtained by the algebraic sum of the items ($\alpha = 0.87$).

2.3. Behavioral procedure

The participants performed a sense of agency paradigm used also in previous studies (Haggard et al., 2002; Voss et al., 2010; Di Plinio et al., 2019a; Di Plinio et al., submitted). On each trial, the participants performed voluntary keypresses with the right index finger while watching a clock hand rotating on a screen. The clock was labeled with numbers positioned at 5-minutes intervals on a standard circular clock. The participants' task was to report the timing of their keypress. In other words, the participants reported the clock time indicated by the clock hand each time they pressed the key. The clock hand rotation began at a random position in each trial and performed a full rotation every 2560 ms. The inter-trial interval was jittered between two and three seconds.

To avoid behavioral biases, the participants were instructed to avoid the planning of their keypresses, to avoid answering in a stereotyped way, and to avoid answering before the end of the first clock rotation. Each participant performed a brief training session before the experiment. The behavioral responses were collected using the E-Prime software (Schneider et al., 2012) while participants were sitting 60 cm from the 20-inches monitor used for the presentation of the stimuli. Sensory feedback used in the present study were acoustic tones. Each tone lasted 200 ms and consisted of a single, continuous pulse at 1000 Hz presented binaurally 250 ms after the keypress. Trials in which the tone was presented were labeled "feedback trials",

while trials in which the tone was not presented were labeled “no-feedback trials”.

Each participant performed five experimental runs in which intentional binding was modulated through the rate of sensory feedback. In two of these runs, there was a probability of 50% for feedback trials: half of the total trials were feedback trials and the remaining half were no-feedback trials. In two other runs, 75% of the trials were feedback trials and the remaining 25% were no-feedback trials. Finally, in one run, there were only no-feedback trials. Each run consisted of 32 trials, for a total of 160 trials. Run order was pseudo-randomized across participants, and trial order was pseudorandomized within each run. Between-run intervals, during which the subject was told to rest, lasted for an average of 28 seconds. The whole procedure lasted approximately 45 minutes for each participant. The task is illustrated in Figure 1.

The perceptual shift (Δ , expressed in milliseconds), namely the difference between the real and the perceived keypress time, was measured for each trial. To note, the perceptual shift and the phenomenon of intentional binding should not be confused. While the former represents the difference between real and perceived keypress time, the latter is a phenomenon that refers to the subjective compression of the time interval between an action and its consequence.

Figure 1. Behavioral task. The participants performed self-decided keypresses with the right index finger while watching a clock hand rotating on a screen. The participants were instructed to judge the clock time when they pressed the key. Auditory feedback (or nothing, contingent on the current trial) was binaurally presented through headphones only in feedback trials, and not in

no-feedback trials. The participants started each trial by pressing a button with the left index finger.

2.4. Statistical analysis

2.4.1. Defining the variable "context"

Our aim was to assess the link between an implicit sense of agency scores (intentional binding calculated through perceptual shifts, Δ) and a temporally dynamic context. Thus, considering the experiment as a unique sequence of feedback and no-feedback trials, we estimated a regressor (parametric modulator), namely *context*, which indicated the proportion of feedback trials in a window of k trials before the ongoing trial. In each participant, for each trial t , we calculated the *context* as

$$C_{k,t} = \frac{F_{k,t} - NF_{k,t}}{(F_{k,t} + NF_{k,t})}$$

where $C_{k,t}$ is the value of the context (standardized proportion of feedback trials before the current trial) for the current trial t ; $F_{k,t}$ is the number of feedback trials among the k trials antecedent the current trial t ; and $NF_{k,t}$ is the number of no-feedback trials among the k trials antecedent the current trial t . Obviously, the first k trials of the experiment were excluded due to the impossibility to have an associated context. Since we wanted to investigate the dynamic effect of the context on intentional binding on multiple temporal scales, values of k were varied in the interval [1-20], with unitary steps. Values of C within each k and within each participant were standardized before further analyses.

2.4.2. Effect of the context on the perceptual shift

Instead of averaging Δ within each block, we performed a trial-based analysis by implementing a mixed-effects multilevel regression model. Within the model, the following variables were considered: the dependent variable was the perceptual shift (Δ); the categorical factor *trial-type* represented the type of trial and therefore could be equal to 'feedback' or 'no-feedback'; the continuous regressor

context was a numerical factor representing the context as the standardized proportion of feedback trials before each trial as described in §2.4.1; finally, *subject* was added as a random grouping factor representing each participant. For each level of the grouping factor *subject* (i.e., for each participant) both a random intercept and random slopes were added to allow the extraction of single-subject estimates (best linear unbiased predictors). A separate model was run for each trial window, that is, for each value of k .

It can be pointed out that a trial-based investigation could suffer from the effects of implicit sensorimotor learning during the task (Taylor et al., 2014; Stark-Inbar et al., 2017). To consider this possible confound, we added a covariate, named *linear trend*, in the model. This covariate represented normalized trial numbers (with a progressive linear increase from 1 to N , where N is the total number of valid trials) and thus accounted for linear trends over time in the perceptual shift (Δ). Another bias in this type of analysis can derive from the presence of outliers in the data. To prevent this issue, for each participant, outlier trials were detected and removed when they differed three scaled median absolute deviations from the median.

2.4.3. Trait factors

The associations between personality traits and the sense of agency on a trial-based approach were investigated following a factor analysis with orthomax rotation using the fourteen original psychometric scales (see §2.2) to obtain orthogonal trait factors (see also Di Plinio et al., 2019a/b). A parallel analysis (Horn, 1965; Ledesma & Valero-Mora, 2007) was implemented to select the number of factors to retain: 10,000 simulated eigenvalues were generated using a Monte Carlo procedure which started from random datasets with equal structure as the original dataset. Then, the number of factors to retain in the factor analysis was selected as the number of eigenvalues above the 95th percentile of the null distribution.

The appropriateness of the factor analysis was tested using a Monte Carlo measurement (1,000 cycles) of Tucker's congruence

coefficient (Korth & Tucker, 1976; Lorenzo-Seva & ten Berge, 2006; de Winter et al., 2009). Within each cycle, the overall sample of 101 participants was randomly split into two subsamples. Tucker's congruence coefficient (K) between the two subsets of factors was estimated in each cycle, and the procedure was repeated using different sample sizes ($N_1 = N_2 = [20, 25, 30, 35, 40, 45, 50]$). Average values of K were calculated, and a hyperbolic trend was fitted to estimate the predicted K based on our overall sample size.

2.4.4. Interactions between trait factors and intentional binding

The associations between personality traits and the sense of agency were investigated after extracting random statistics from the mixed-effects model described in section §2.4.2. For each possible effect of interest (i.e., *trial-type*, *context*, and the interaction *context:trial-type*), the best linear unbiased predictor (BLUP) was extracted from each subject and then the group effect was added to obtain individual estimates of the effect (β_T , β_C , $\beta_{C \times T}$). This procedure was repeated for each trial window k .

Subsequently, a multivariate regression model was run for each effect of interest. The dependent variable was represented by the individual estimates in the 20 different trial windows. The five psychometric factors resulting from the factor analysis (F1-5) were used as continuous regressors. To note, since the orthomax rotation was used to obtain orthogonal trait factors, these analyses do not entail collinearity issues. Results were corrected for multiple comparisons using false discovery rate.

3. RESULTS

3.1. Effect of the context on the perceptual shifts

The results and statistics of the trial-based analysis are reported in Figure 2 and Table I. The main effect of *trial-type*, indicating the retrospective component, was significant across all the trial windows explored (Figure 2a). Instead, the main effect of the *context*

alone, reflecting a prospective component, was significant when the context was estimated by using a trial window of 7 or more prior trials (Figure 2b). There also was a significant interaction between context and trial-type (Figure 2c) that changed dynamically depending on the size of the trial window. Specifically, context and trial type interacted when the context was estimated using trial windows comprised between 1 to 6 trials. This interaction was not significant anymore when the context was estimated using trial windows comprised between 7 to 20 trials. Residuals were normally distributed and there were no differences between residuals from feedback vs. no-feedback trials as reported in Figure 2d.

Figure 2. Results of the trial-based analysis. Group beta estimates and standard errors for the effect of trial-type (a), context (b), and for the interaction context:trial-type (c) derived from multilevel regression models. Significant results are indicated by more intense color bars and asterisks (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). (d) Residuals for each regression model. Residuals (in milliseconds) related to feedback and no-feedback trials are reported in blue and red colors, respectively. The substantial overlap is evident.

The essence of the interaction between *context* and *trial-type* is illustrated in Figure 3, in which predictions relative to feedback and no-feedback trials with respect to the context are illustrated for increasing trial window lengths. In the case of no-feedback trials and with a narrower trial window size (orange colors in Figure 3a), individuals shifted their perception towards the expected temporal position of the tone within contexts of high-tone probability.

Figure 3. Interaction context:trial-type. The figure displays predictions of the perceptual shift in no-feedback trials (a) and feedback trials (b), using varying levels of context and trial windows. A narrow context (calculated using 1-6 trials) had a large positive effect on no-feedback trials and no effect (or a slightly negative effect) on feedback trials, reflecting the significance of the interaction context:trial-type. Instead, an extended context (estimated using 7-20 trials) had a moderate, positive effect on both no-feedback and feedback trials (grey lines in both subfigures), reflecting the significance of the factor context.

Thus, when considering narrow trial windows, there was a strong effect of the context on the perceptual shifts for the no-feedback trials. Instead, this trend was no longer observed for the same trial window lengths during the feedback trials (blue colors in Figure 3b). In fact, the low versus high probability of action feedback had almost no impact on intentional binding in feedback trials. On the other

hand, when the context was estimated using extended trial windows (i.e., 7-20 trials), the context showed a moderate positive association with the perceptual shifts in both feedback and no-feedback trials, without distinction (grey lines in Figure 3a-b).

3.2. Trait factor results

The parallel analysis indicated five factors to use, as this was the number of eigenvalues above the 95th percentile from the null distribution (Figure 4a; see also Di Plinio et al., 2019a/b). The Monte Carlo procedure for computing Tucker's congruence coefficient highlighted a high consistency for the factor analysis ($K \sim 0.95$, Figure 4b). The score distributions of the five factors extracted in this way are reported in Figure 4c. Average scores, standard deviations, and ranges for all original subscales are reported in Table II. The following subscales had the highest loadings: (F1) STAI2, IUS-inhibitory, CAPE-depression, BFI-neuroticism (negative affect trait); (F2) SPQ-cognitive-perceptual, CAPE-positive, CAPE-negative (psychosis-like experiences trait); (F3) IUS-prospective, BFI-extraversion, BFI-agreeableness, BFI-openness (positive sociality trait); (F4) SPQ-interpersonal, SPQ-disorganization (schizotypal trait); (F5) BFI-conscientiousness.

Figure 4. Factor analysis. (a) Eigenvalues distributions from the parallel analysis indicated five factors to retain in the factor analysis. (b) The analysis of Tucker's congruence coefficient suggested a high consistency of the factor analysis. (c) The distribution of scores across the 61 subjects used in this study is shown for each factor.

3.3. Relationships between sense of agency and psychometric factors

Associations between the five psychometric factors and the three effects of the multilevel regression models (*trial-type*, *context*, *context:trial-type*) were evaluated using multivariate models. Only one effect was significant after the correction for multiple comparisons: the psychometric factor F2 (related to psychosis-like experiences) was negatively associated with the strength of the interaction *context:trial-type*, especially when the trial windows for the estimation of the context were comprised between 1 and 6 trials ($F_{(19)} = 3.1$; $p = 9.1e-06$; multivariate model). Figure 5 reports this result, showing that the *context:trial-type* interaction in a narrow context (trial window < 6 prior events) was strong in individuals with low scores in psychosis-like experience traits, but was weaker with higher scores in these traits.

Figure 5. Effect of the factor F2 on perception. The figure displays the significant result among multivariate models after corrections for multiple comparisons. Green and purple colors indicate individuals with low and high scores in F2, respectively. As shown in the figure, low scorers in F2 exhibit a strong *context:trial-type* interaction with a narrow trial window comprised between 1 and 6 trials (green colors), while this interaction tends to become irrelevant in high scorers (purple colors; ***: $p = 9.1e-06$).

4. DISCUSSION

The present study investigated the prospective and retrospective components of the implicit sense of agency using multiple temporal scales to define the context and implementing a trial-based approach. In particular, we defined the context as the proportion of feedback trials preceding each trial. Our findings showed that an extended, less recent context (considering 7 to 20 trials prior to the actual trial) had a moderate effect on the prospective sense of agency. This contextual effect was independent of trial type, that is, the presence or absence of the sensory feedback. By contrast, a narrow, more recent context (1 to 6 trials prior to the actual trial) had a strong effect on the prospective sense of agency only when the trial type conflicted with the context, that is, when no-feedback trials occurred in the context of a high probability of feedback occurrence. Thus, trial type interacts with prospective intentional binding effects based on a recent context, but not when based on an extended, less recent context. The strength of this interaction between trial type and context was

negatively associated with psychosis-like experience trait scores. Considering previous literature on the sense of agency (Moore, 2016; Haggard, 2017; Bandura, 2018), we suggest that context-related effects in our study are associated with prospective and attentional-perceptual agency mechanisms, because the retrospective sense of agency represents inferential, purely outcome-dependent processes.

Nevertheless, we also found a significant retrospective component represented by the difference in the perception of feedback vs. no-feedback trials, as indicated by the significance of the factor *trial-type* across all the trial windows. Feedback trials elicited stronger intentional binding, with a perceptual shift (Δ) closer to zero compared to no-feedback trials. Although this may appear in disagreement with findings of a nonsignificant retrospective sense of agency using the same paradigm (Voss et al., 2010), a small though statistically nonsignificant retrospective component was found in previous investigations (Di Plinio et al., 2019a; Di Plinio, Perrucci, & Ebisch, submitted). Such a retrospective effect is consistent with, and expands, current models of the sense of agency, showing its independence from narrow as well as extended contexts (Synofzik et al., 2008, 2013). We suggest that a significant retrospective effect in our study was detected by an accurate modeling of the response variable. This finding was made possible by considering the interaction between retrospective and prospective intentional binding effects, by including a relatively large number of participants, and by implementing a multilevel mixed-effects regression model.

Regarding prospective processes, previous studies have shown that a dynamic, evolving context conceivably influences the sense of agency through the dynamic modulation of predictive mechanisms (Wolpert et al., 2011; Clark, 2013) instantiated in sensorimotor and executive brain networks (Gallese & Sinigaglia, 2010; Di Plinio et al., 2019b). As suggested by existing models of the sense of agency (Friston & Kiebel, 2009; Friston, 2012; Thilakaratne & Treur, 2015; Buhrmann & Di Paolo, 2017; Legaspi & Toyoizumi, 2019), these predictive mechanisms are putatively mediated by implicit sensorimotor learning (McDougle et al., 2016; Kim et al., 2019). On the one hand, we confirmed the existence of a classic, prospective sense of agency

1 in our experiment (Haggard et al., 2002; Moore & Haggard, 2008; Voss
2 et al., 2010; Synofzik et al., 2008, 2013). This context was
3 established by trials within a temporally extended context of action
4 feedback. In this case, intentional binding (and thus the sense of
5 agency) was increased with a higher probability of sensory
6 consequences. Interestingly, this contextual effect was equally
7 observable in feedback trials and no-feedback trials and can therefore
8 be considered independent of the actual action consequence.

9 On the other hand, the sense of agency based on a *narrow* context
10 of the online experience was influenced by the current *trial type*. In
11 fact, we found an interaction between context and trial-type within a
12 narrow context of action feedback: a high probability of tones in a
13 window of less than seven prior trials increased intentional binding
14 when the expected action feedback was missing, that is, in no-feedback
15 trials. This suggests that a recent, high-probability context of
16 agency generates a robust expectation and that a conflicting event
17 (missing feedback) increases intentional binding effects. We
18 hypothesize that such interaction may depend on both attentive and
19 perceptual-cognitive processes, as follows. First, a narrow high-tone-
20 probability context implies an increased rate of physical interactions
21 between the participant and the environment. This increases the
22 participant's engagement and externally oriented attention (Schooler
23 et al., 2011; Di Plinio et al., 2019a), possibly causing a shift of
24 the perception toward the expected tone (Correa et al., 2006; Burgess
25 et al., 2019). Second, the interaction between context and trial-type
26 may rely on perceptual Bayesian-like processes underlying sensorimotor
27 learning: when a strong prediction is generated, brain predictive
28 coding mechanisms enhance the expectation that the action consequence
29 *is going to happen*, and this expectancy might then be sustained over
30 time (De Ridder et al., 2014; Parr et al., 2019). Consequently, the
31 median expectation of the sensory consequence is delayed. In other
32 words, in the case of strongly expected missing feedback, the time
33 window during which the individual waits for feedback is stretched,
34 ultimately resulting in a shift of the temporal estimate toward the
35 expected feedback.

Notably, psychosis-like experience traits (F2) were associated with the strength of the interaction *context:trial-type* (i.e., the strength of the interaction of predictive and retrospective sense of agency components) within a narrow context. In particular, psychosis-like experience traits negatively correlated with intentional binding effects when action feedback was lacking and when a narrow context suggested a high probability for feedback. Thus, intentional binding is modulated when the current trial type conflicts with the narrow context in individuals with low levels of psychosis-like traits. This possibly favors a flexible sensorimotor learning based on recent and current evidence. By contrast, individuals with high levels of psychosis-like traits may need more time or more evidence to adapt to a dynamically evolving context. This finding agrees with previous reports of both behavioral (Moore et al., 2011) and neural (Williams, et al., 2013; Giersch, et al., 2016) evidence aberrant habituation in schizophrenic patients. Previous studies have also found that deficiency of motor adaptation correlates with positive clinical symptoms in schizophrenia (Linney et al., 1998; Van Dael et al., 2006; Garety et al., 2011; Bansal et al., 2019). These effects are probably related to an impaired implicit learning of new rules or contexts (Frith et al., 2000; Blakemore et al., 2002; Ford & Mathalon, 2005; Hauser et al., 2011; Martinelli et al., 2017) and may be exacerbated in situations of diminished environmental control, ambiguity, and unpredicted events (Moore et al., 2011; Gallagher & Trigg, 2016, Di Plinio et al., 2019a, 2019b).

To summarize, we maintain that psychosis-like traits are associated with less efficient sensorimotor predictions and a reduction in the adaptability of the subjective sense of agency to ongoing sensory experience. We suggest that previous findings of psychotic or schizotypal traits during the manipulation of the sense of agency (Voss et al., 2010; Hauser et al., 2011; Moore & Fletcher, 2012; Martinelli et al., 2017; Di Plinio et al., 2019a) could be related to the interaction between prospective and retrospective features. Contemplating such an effect in the Bayesian-like framework highlighted above, we hypothesize that the expectation enhancement in a narrow high-probability context is weakened in participants with increased psychosis-like experiences because of aberrant sensorimotor

adaptation to the external environment. Figure 6 provides a graphical representation of this effect. Our findings trace a link between personality traits and the emerging sense of agency, suggesting that psychotic traits may undermine the updating of predictive sensorimotor

mechanisms also in healthy individuals.

Figure 6. Bayesian interpretation of the effect of psychosis-like traits on intentional binding for narrow contexts. According to the model, in the case of missing feedback, the median expectation for that feedback is protracted over time within a narrow high-probability context (left panel, dashed line) but not within a narrow low-probability context of agency (left panel, continuous line). This implies a shift forward in the perceived timing of the action, represented by a greater intentional binding in our study. Instead, with increasing scores in psychotic traits (central and right panel), this expectation is no longer generated; the interaction effect is reduced as reflected by a decreased intentional binding for the narrow high-probability context, possibly as a consequence of impaired sensorimotor adaptation.

Our study has some limitations. For example, context-specific interactions between prospective and retrospective sense of agency were only assessed in the classic rotating clock experiment. However, recent studies have reported local and global temporal effects on implicit learning at both the neural and behavioral levels (Correa et al., 2006; Rolke & Hofmann, 2007; Ball et al., 2018; Burgess et al., 2019), supporting the generalization of our findings across diverse sense of agency paradigms. Furthermore, we investigated implicit but not explicit (Haggard, 2017; Imaizumi & Tanno, 2019) measures of the sense of agency, which are known to be at least partially divergent (Moore et al., 2012). Future studies may benefit from considering large samples to test time-dependent and context-dependent effects on

both implicit and explicit agency dimensions, alongside classic run-based approaches.

5. CONCLUSION

Our findings revealed that prospective mechanisms of the sense of agency can be retrospectively influenced by the nature of the ongoing event, suggesting that predictive mechanisms rely on multiple temporal scales. In view of our findings, future cognitive models of agency should integrate the dynamic interplay between internally generated predictions and sensorimotor interactions to explain the processes underlying the human sense of agency. Through the investigation of interindividual differences in a large sample, our findings also have clinical implications. We found that high scores in psychosis-like experience traits in a non-clinical sample are associated with reduced intentional binding effects in a narrow context of prospective sense of agency, indicating weaker attentive-perceptual sensorimotor adaptation. This lack of adaptation plausibly parallels the difficulties in adapting to social contexts that accompany high schizophrenic traits (de Bézenac, et al., 2015; van der Weiden, et al., 2015), which possibly threatens the subjective sense of self as a social agent during social interactions. Future studies are needed to clarify whether such findings in individuals with high psychosis-like traits are rooted in reduced habituation mechanisms, if they are a consequence of a decreased exogenous attention, or if they reflect abnormal predictive processes. Based on our findings, we suggest that all these mechanisms may be critically involved.

TRIAL WINDOW	Trial-type		Context		Interaction	
	β	pValue	β	pValue	β	pValue
1	-5.9	<.001	-0.7	.49	5.4	<.001
2	-6.0	<.001	0.0	.96	3.5	<.001
3	-6.2	<.001	0.5	.33	2.0	.003
4	-5.9	<.001	0.7	.13	1.3	.022
5	-5.9	<.001	0.7	.069	1.0	.033
6	-5.6	<.001	0.6	.077	0.9	.030
7	-5.8	<.001	0.7	.036	0.7	.062
8	-5.8	<.001	0.7	.023	0.5	.13
9	-5.8	<.001	0.6	.018	0.4	.16
10	-5.9	<.001	0.7	.005	0.3	.35
11	-5.9	<.001	0.7	.004	0.2	.40
12	-5.9	<.001	0.6	.003	0.2	.37
13	-5.7	<.001	0.6	.004	0.2	.36
14	-5.8	<.001	0.5	.004	0.2	.31
15	-5.7	<.001	0.5	.003	0.2	.30
16	-5.8	<.001	0.5	.006	0.3	.19
17	-5.8	<.001	0.4	.007	0.2	.22
18	-5.8	<.001	0.3	.023	0.3	.08
19	-5.7	<.001	0.3	.019	0.3	.10
20	-5.7	<.001	0.4	.009	0.3	.12

Table I. Statistics of the trial-based analyses. Beta estimates and p values for the three effects, i.e., *trial-type*, *context*, and the interaction *context:trial-type*. Significant results are highlighted in bold font. Non-significant results are shaded (threshold: $p < 0.05$, uncorrected).

	F1	F2	F3	F4	F5
SPQ-INTERPERSONAL	.27	.25	-.39	.84	-.02
SPQ-DISORGANIZED	.32	.36	.17	.57	-.16
SPQ-COGNITIVE	.20	.68	-.15	.39	-.04
CAPE-POSITIVE	.05	.98	-.12	.10	-.07
CAPE-NEGATIVE	.34	.44	-.22	.34	-.30
CAPE-DEPRESSIVE	.79	.37	.01	.16	-.18
STAI-TRAIT	.81	.11	-.13	.16	-.19
IUS-INHIBITORY	.47	.03	-.34	.26	-.26
IUS-PROSPECTIVE	.26	.20	-.48	.02	.09
BFQ-EMOT.STABILITY	-.69	-.01	.29	-.16	-.07
BFQ-EXTRAVERSION	-.36	.26	.49	-.21	.15
BFQ-AGREEABLENESS	.03	-.09	.50	-.12	.11
BFQ-OPENNESS	-.21	-.08	.61	.06	.33
BFQ-CONSCIENTIOUSNESS	-.15	-.09	.20	-.09	.78

Table II. Questionnaire contributions to psychometric factors. Bold values indicate scales with a large contribution to a specific factor (eigenvalue > 0.40). Shading indicates scales with a small contribution to a specific factor (eigenvalue < 0.30). SPQ = Schizotypal Personality Questionnaire; CAPE = Community Assessment of Psychic Experience; STAI = State-Trait Anxiety Inventory; IUS = Intolerance of Uncertainty Scale; BFQ = Big Five Questionnaire.

REFERENCES

- Asai, T, Sugimori, E, Tanno, Y (2008). Schizotypal personality traits and prediction of one's own movements in motor control: What causes an abnormal sense of agency? *Consciousness and Cognition*, 17(4):1131-1142.
- Asai, T, Sugimori, E, Bando, N, Tanno, Y (2011). The hierarchic structure in schizotypy and the five-factor model of personality. *Psychiatry Research*, 185(1-2), 78-83.
- Ball, F, Fuehrmann, F, Stratil, F, Noesselt, T (2018). Phasic and sustained interactions of multisensory interplay and temporal expectation. *Scientific Reports*, 8(1), 1-12.
- Bandura, A (2018). Toward a psychology of human agency: Pathways and reflections. *Perspectives in Psychological Science*. 13(2), 130-136.
- Bansal, S, Murthy, KG, Fitzgerald, J, Schwartz, BL, Joiner, WM (2019). Reduced transfer of visuomotor adaptation is associated with aberrant sense of agency in schizophrenia. *Neuroscience*, 413, 108-122.
- Berberian, B, Sarrazin, JC, Le Blaye, P, Haggard, P (2012). Automation technology and sense of control: a window on human agency. *PLoS One*, 7(3):e34075.
- Blakemore, SJ, Wolpert, DM, Frith, CD (2002). Abnormalities in the awareness of action. *Trends in Cognitive Sciences*, 6, 237-242.
- Bohrani, K, Beck, B, Haggard, P (2017). Choosing, doing, and controlling: Implicit sense of agency over somatosensory events. *Psychological Science*, 28(7), 882-893.
- Buhrmann, T, Di Paolo, E (2017). The sense of agency - A phenomenological consequence of enacting sensorimotor schemes. *Phenomenology and the Cognitive Sciences*, 16(2), 207-236.
- Burgess, JD, Major, BP, McNeel, C, Clark, GM, Lum, JAG, Enticoot, PG (2019). Learning to expect: Predicting sounds during movement is related to sensorimotor association during listening. *Frontiers in Human Neuroscience*, 13(215), 1-14.
- Caprara, GV, Barbaranelli, C, Borgogni, L, Perugini, M (1993). The "Big Five Questionnaire": A new questionnaire to assess the five factor model. *Personality and Individual Differences*, 15(3), 281-288.
- Carleton, RN, Norton, MA, Asmundson, GJG (2007). Fearing the unknown: A short version of the intolerance of uncertainty scale. *Journal of Anxiety Disorders*, 21, 105-117.
- Clark, A (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, 36(3), 181-204.
- Correa, À, Lupiáñez, J, Madrid, E, Tudela, P (2006). Temporal attention enhances early visual processing: A review and new evidence from event-related potentials. *Brain Research*, 1076, 116-128.
- Costa, PT, McCrae, RR (1985). The NEO personality inventory manual. Odessa, FL: Psychological Assessment Resources.
- Desantis, A, Waszak, F, Moutsopoulou, K, Haggard, P (2016). How action outcome structures time: About the perceived temporal order of action and predicted outcomes. *Cognition*, 146, 100-109.
- de Bézenac, CE, Sluming, V, O'Sullivan, N, Corcoran, R (2015). Ambiguity between self and other: Individual differences in action attribution. *Consciousness and Cognition*, 35, 1-15.
- De Ridder, D, Vanneste, S, Freeman, W (2014). The Bayesian brain: Phantom percepts resolve sensory uncertainty. *Neuroscience and Biobehavioral Reviews*, 44, 4-15.
- de Winter, JCF, Dodou, D, Wiering, PA (2009). Exploratory factor analysis within small sample sizes. *Multivariate Behavioral Research*, 44(2), 147-181.
- Di Plinio, S, Arnò, S, Perrucci, MG, Ebisch, SJH (2019a). Environmental control and psychosis-relevant traits modulate the prospective sense of agency in non-clinical individuals. *Consciousness and Cognition*, 73, 102776.

- 1 Di Plinio, S, Perrucci, MG, Aleman, A, Ebisch, SJH (2019b). I am Me: Brain systems
2 integrate and segregate to establish a multidimensional sense of self.
3 *NeuroImage*, 205, 116284.
- 4 Di Plinio, S, Perrucci, MG, Ebisch, SJH (2019). The prospective sense of agency is
5 rooted in local and global properties of intrinsic functional brain networks.
6 Submitted.
- 7 Dogge, M, Custers, R, Gayet, S, Hoijsink, H, Aarts, H (2019). Perception of action-
8 outcome is shaped by life-long and contextual expectations. *Scientific Reports*,
9 9(1), 5225.
- 10 Ford, JM, Mathalon, DH (2005). Corollary discharge dysfunction in schizophrenia:
11 Can it explain auditory hallucinations? *International Journal of*
12 *Psychophysiology*, 58, 179-189.
- 13 Fossati, A, Raine, A, Carretta, I, Leonardi, B, Maffei, C (2003). The three-factor
14 model of schizotypal personality: Invariance across age and gender . *Personality*
15 *and Individual Differences*, 35(5), 1007-1019.
- 16 Friston, K, Kiebel, S (2009). Predictive coding under the free-energy principle.
17 *Philosophical Transactions of the Royal Society B: Biological Sciences*,
18 364:1211-1221.
- 19 Friston, K (2012). Prediction, perception and agency. *International Journal of*
20 *Psychophysiology*, 83(2), 248-252.
- 21 Frith, CD, Blakemore, S, Wolpert, DM (2000). Explaining the symptom of
22 schizophrenia: Abnormalities in the awareness of action. *Brain Research Reviews*,
23 31, 357-363.
- 24 Gallagher, S, Trigg, D (2016). Agency and Anxiety: Delusions of control and loss of
25 control in Schizophrenia and Agoraphobia. *Frontiers in Human Neuroscience*, 10,
26 459.
- 27 Gallese, V, Sinigaglia, G (2010). The bodily self as power for action.
28 *Neuropsychologia*, 48(3), 746-755.
- 29 Garety, P, Freeman, D, Jolley, S, Ross, K, Waller, H, Dunn, G (2011). Jumping to
30 conclusions: the psychology of delusional reasoning, *Advances in Psychiatric*
31 *Treatment*, 17, 332-339.
- 32 Giersch, A, Lalanne, L, Isope, P (2016). Implicit timing as the missing link
33 between neurobiological and self disorders in schizophrenia? *Frontiers in Human*
34 *Neuroscience*, 10, 103.
- 35 Haggard, P, Clark, S, Kalogeras, J (2002). Voluntary action and conscious
36 awareness. *Nature Neuroscience*, 5(4):382.
- 37 Haggard, P (2017). Sense of agency in the human brain. *Nature Reviews Neuroscience*,
38 18(4):196.
- 39 Hauser, M, Knoblich, G, Repp, BH, Lautenschlager, M, Gallinat, J, Heinz, A, Voss, M
40 (2011). Altered sense of agency in schizophrenia and the putative psychotic
41 prodrome. *Psychiatry Research*, 186(2-3), 170-176.
- 42 Horn, JL (1965). A rationale and test for the number of factors in factor analysis.
43 *Psychometrika*, 30(2), 179-185.
- 44 Imaizumi, S, Tanno, Y (2019). Intentional binding coincides with explicit sense of
45 agency. *Consciousness and Cognition*, 67:1-15.
- 46 Jeannerod, M (2009). The sense of agency and its disturbances in schizophrenia: A
47 reappraisal. *Experimental Brain Research*, 192(3), 527.
- 48 Kim, HE, Parvin, DE, Ivry, RB (2019). The influence of task outcome on implicit
49 motor learning. *Elife*, 8, e39882.
- 50 Konings, M, Bak, M, Hanssen, M, van Os, J, Krabbendam, L (2006). Validity and
51 reliability of the CAPE: A self-report instrument for the measurement of
52 psychotic experiences in the general population. *Acta Psychiatrica Scandinavica*,
53 114(1), 55-61.
- 54 Korth, B, Tucker, LR (1976). Procrustes matching by congruence coefficients.
55 *Psychometrika*, 41(4), 531-535.

- 1 Kumar, D, Srinivasan, N (2013). Hierarchical control and sense of agency:
2 Differential effects of control on implicit and explicit measures of agency.
3 *Proceedings of the Annual Meeting of the Cognitive Science Society*. 35(35).
- 4 Ledesma, RD, Valero-Mora, P (2007). Determining the number of factors to retain in
5 EFA: An easy-to-use computer program for carrying out parallel analysis.
6 *Practical assessment, Research & Evaluation*, 12(2), 2-11.
- 7 Legaspi, R, Toyoizumi, T (2019), A bayesian psychophysics model of sense of agency.
8 *Nature Communications*, 10(4250).
- 9 Linney, YM, Peters, ER, Ayton, P (1998). Reasoning biases in delusion-prone
10 individuals. *British Journal of Clinical Psychology*, 37, 285-302.
- 11 Lorenzo-Seva, U, ten Berge, JMF (2006). Tucker's congruence coefficient as a
12 meaningful index of factor similarity. *Methodology: European Journal of Research*
13 *Methods for the Behavioral and Social Sciences*, 2(2), 57-64.
- 14 Martinelli, C, Rigoli, F, Shergill, SS (2017). Aberrant force processing in
15 schizophrenia. *Schizophrenia Bulletin*, 43, 417-424.
- 16 McDougle, SD, Ivry, RB, Taylor, JA (2016). Taking aim at the cognitive side of
17 learning in sensorimotor adaptation tasks. *Trends in Cognitive Sciences*, 20(7),
18 535-544.
- 19 Moore, JW, Haggard, P (2008). Awareness of action: Inference and prediction.
20 *Consciousness and Cognition*. 17(1), 136-144.
- 21 Moore, JW, Dickinson, A, Fletcher, PC (2011). Sense of agency, associative
22 learning, and schizotypy. *Consciousness and Cognition*, 20, 792-900.
- 23 Moore, JW, Middleton, D, Haggard, P, Fletcher, PC (2012). Exploring implicit and
24 explicit aspects of sense of agency. *Consciousness and Cognition*, 21(4), 1748-
25 1753.
- 26 Moore, JW, Fletcher, PC (2012). Sense of agency in health and disease: A review of
27 cue integration approaches. *Consciousness and Cognition*, 21, 59-68.
- 28 Moore, JW (2016). What is the sense of agency and why does it matter? *Frontiers in*
29 *Psychology*, 7, 1272.
- 30 Parr, T, Corcoran, AW, Friston, KJ, Hohwy, J (2019). Perceptual awareness and
31 active inference. *Neuroscience of Consciousness*, 2019(1), niz012.
- 32 Raine, A (1991). The SPQ: A scale for the assessment of schizotypal personality
33 based on DSM-III-R criteria. *Schizophrenia Bulletin*, 17(4), 555-564.
- 34 Rolke, B, Hofmann, P (2007). Temporal uncertainty degrades perceptual processing.
35 *Psychonomic Bulletin and Review*, 14(3), 522-526.
- 36 Schneider, W, Eschman, A, Zuccolotto, A (2012). E-Prime 2.0 Reference Guide Manual.
37 Pittsburgh: Psychology Software Tools Inc.
- 38 Schooler, JW, Mrazek, MD, Franklin, MS, Baird, B, Mooneyham, BW, Zedelius, C,
39 Broadway, JM (2014). The middle way. *Psychology of Learning and Motivation*
40 (Elsevier), Burlington: Academic Press, 1-33.
- 41 Sidarus, N, Vuorre, M, Haggard, P (2017). Integrating prospective and retrospective
42 cues to the sense of agency: A multi-study investigation. *Neuroscience of*
43 *Consciousness*, 1, niz012.
- 44 Spielberger, CD, Gorsuch, RL, Lushene, PR, Vagg, PR, Jacobs, GA (1983). Manual for
45 the state-trait anxiety inventory. Consulting Psychologists Press.
- 46 Stark-Inbar, A, Raza, M, Taylor, JA, Ivry, PB (2017). Individual differences in
47 implicit motor learning: Task specificity in sensorimotor adaptation and
48 sequence learning. *Journal of Neurophysiology*, 117(1), 412-428.
- 49 Synofzik, M, Vosgerau, G, Newen, A (2008). Beyond the comparator model: A
50 multifactorial two-step account of agency. *Consciousness and Cognition*, 17(1),
51 219-239.
- 52 Synofzik, M, Vosgerau, G, Voss, M (2013). The experience of agency: An interplay
53 between prediction and postdiction. *Frontiers in Psychology*, 4, 127.

- 1 Taylor, JA, Krakauer, JW, Ivry, PB (2014). Explicit and implicit contributions to
2 learning in a sensorimotor adaptation task. *Journal of Neuroscience*, 34(8),
3 3023-3032.
- 4 Thilakaratne, DJ, Treur, J (2015). Computational cognitive modelling of action
5 awareness: Prior and retrospective. *Brain Informatics*, 2(2), 77-106.
- 6 Van Dael, F, Versmissen, D, Janssen, I, Myin-Germeys, I, van Os, J, Krabbendam, L
7 (2006). Data gathering: biased in psychosis? *Schizophrenia Bulletin*, 32, 341-
8 351.
- 9 van der Weiden, A, Prikken, M, van Haren, NE (2015). Self-other integration and
10 distinction in schizophrenia: A theoretical analysis and a review of the
11 evidence. *Neuroscience and Biobehavioral Reviews*, 57, 220-237.
- 12 Van Kemenade, BM, Arikan, BE, Kircher, T, Straube, B (2016). Predicting the sensory
13 consequences of one's own action: First evidence for multisensory facilitation.
14 *Attention Perception Psychophysics*, 78(8), 2515-2526.
- 15 Voss, M, Moore, J, Hauser, M, Gallinat, J, Heinz, A, Haggard, P (2010). Altered
16 awareness of action in schizophrenia: a specific deficit in predicting action
17 consequences. *Brain*, 133(10), 3104-3112.
- 18 Wen, W (2019). Does delay in feedback diminish the sense of agency? A review.
19 *Consciousness and Cognition*, 73(192759), 1-9.
- 20 Williams, LE, Blackford, JU, Luksik, A, Gauthier, I, Heckers, S (2013). Reduced
21 habituation in patients with schizophrenia. *Schizophrenia Research*, 151(0), 124-
22 132.
- 23 Wolpert, DM, Diedrichsen, J, Flanagan, J R (2011). Principles of sensorimotor
24 learning. *Nature Reviews Neuroscience*, 12(12), 739-751.