PERCEIVED AGENCY AND THE PRE-FEEDBACK DELAY:
A TIME-FREQUENCY ANALYSIS

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PERCEIVED AGENCY AND THE PRE-FEEDBACK DELAY:

A TIME-FREQUENCY ANALYSIS

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DEDICATION

If I had all the time or ink in the world, it would still not be enough to thank all of the loved ones whose support, advice, and affirmations brought me here. I would first like to thank my mum and dad, who helped instill in me a love of learning (and psychology!) and gave me the tools I needed to study well while still caring for myself. Your encouragement of my goals and my writing has blessed me in more ways than you could possibly imagine. To my sisters, thank you for many hours of laughter, for all the witty jokes and cute cat pictures that sustained me through the long hours of writing and stressing over deadlines. And finally, my eternal gratitude to my fiancé and soon-to-be husband, whose unwavering support throughout the entire process was one of the main factors in keeping my sanity safely intact. I love you.
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ABSTRACT

In everyday life, it is often the case that an individual must reflect on which, if any, of their actions led to a favorable or unfavorable outcome, especially if a sizeable period of time passed prior to knowing the outcome. If they attribute these outcomes to themselves, rather than to some external source, they would be said to have a “sense of agency.” As of this paper, only event-related potentials and fMRI methods have been used to assess this phenomenon. In this experiment, we re-analyzed the data from a previous SPN study using a more powerful analytic method, time-frequency analysis, and tested a variety of hypotheses concerning previously established relationships between oscillatory activity and brain regions involved in feedback anticipation. Participants took part in a gambling task where their “sense of agency” and the valence of the expected outcome (potential loss versus potential gain) were manipulated. In choice trials, it was implied that participants’ decisions influenced whether they won or lost money, while in no-choice trials, participants were correctly informed that the computer determined these outcomes. We found that pre-feedback alpha suppression in sites overlying right frontal and occipital areas was stronger on choice trials. Pre-feedback beta suppression in sites overlying left frontal sites was also greater on these trials. Both of these effects appeared to be modulated by contextual valence—effects were significantly larger in conditions with potential gain than those involving potential loss. These findings highlight the importance of selective attention and reward anticipation when the outcome of one’s own action is awaited.

Keywords: stimulus-preceding negativity (SPN), electroencephalography (EEG), sense of agency, time-frequency analysis, pre-feedback delay, contextual valence
INTRODUCTION

The way that individuals learn from their actions is through feedback, which gives valuable insight into what one did poorly, what one did well, and how to optimize future attempts. However, feedback is not always given directly after one makes an action, and in fact very often occurs after some time has passed. Thus, one is placed in the position of trying to figure out exactly which of their actions (if any) contributed to a favorable or unfavorable outcome. This is referred to as the credit assignment problem (Minsky, 1961). In order to learn in situations when feedback is delayed, Sutton and Barto (1998) proposed the idea of an eligibility trace—a kind of mental representation of the action and external circumstances that led to the feedback. This representation allows one to compare the expected outcome of their actions to their actual outcome, and assign credit, if it is warranted. For this to work, one has to be sure that they are the agent of that action.

The Stimulus-Preceding Negativity (SPN)

The present work is a reanalysis of a study by Hackley and colleagues (2020) that analyzed an EEG component called the stimulus-preceding negativity (SPN) in order to assess the effects of agency in a gambling task. The decision to study the SPN’s sensitivity to agency and related phenomena was based on a number of previous experiments. Much early work demonstrated that the SPN is anticipatory, as it is a slow negative wave that ramps upward in the delay during which one is anticipating a stimulus (van Boxtel & Böcker, 2004; Damen & Brunia, 1987). However, as an increasing number of studies were performed, it became apparent that labeling the SPN as mere anticipation was not the whole picture. For instance, in a study by Damen and Brunia (1994), the authors investigated whether anticipation of different types of task-related stimuli (feedback versus instructions for the next trial) elicited an SPN. They found
that mere task relevance was not sufficient, and it was only feedback on task performance that produced a clear SPN. This finding was later replicated by other researchers (Böcker et al., 1994). Another study found that if feedback was more relevant and detailed, the amplitude of the SPN was larger (Kotani et al., 2003).

Because the SPN is produced by the anticipation of motivationally relevant stimuli, such as feedback on one’s performance, it may be a useful tool in understanding feedback learning (Brunia et al., 2011), including credit assignment (Bhangal et al., 2021; Ren et al., 2017). A trait of the SPN that is particularly relevant to this thesis is that it has larger amplitudes if participants believe they have more control or involvement over their outcomes (Kotani et al., 2017; Masaki et al., 2010). For example, previous studies have demonstrated that participants exhibited significantly larger SPNs while waiting for feedback on a decision they believed they had made themselves than when they were waiting for feedback on a decision they believed a computer had made for them (Hackley et al., 2020; Masaki et al., 2010). If the SPN was only an indicator of anticipation, or just anticipation of a salient or emotion-inducing stimulus, it would be reasonable to expect no difference between these conditions. Because there was a significant difference, this shows that the SPN is relevant to the problem of agency.

The Problem of Agency

In order for feedback- or reinforcement-based learning to take place, one must first be able to determine whether or not an outcome occurred due to one’s own actions or due to some external source. The previously mentioned paper by Masaki, Yamazaki, and Hackley (2010) is directly relevant to the present study, so it is pertinent to go over their experimental methods in greater detail. In that study, subjects participated in a gambling task with two conditions. In the choice condition, participants were led to believe that they had agency—that the decision they
made through a key-pressing response influenced their monetary gain or loss in each trial, whereas in the no-choice condition, they were (correctly) told that the gain or loss was determined at random by the computer. Unbeknownst to the participants, the gain or loss happened at random in both conditions, unaffected by their key-pressing. Masaki and colleagues found that pre-feedback SPNs in the choice condition were more than double the size of those in the no-choice condition, with the greatest difference being found at right prefrontal sites.

Abundant research utilizing brain imaging has also identified greater activation at right prefrontal sites related to a sense of agency, along with several other brain regions. However, these studies have only rarely included a delay period prior to feedback, and so are of limited value towards understanding the credit assignment problem. The current study is a reanalysis of a paper by Hackley and coauthors (2020), which had methods very similar to those of Masaki and colleagues (2010; see also Mei et al., 2018). These studies used a gambling task with a pre-feedback delay period, and aimed to study the SPN as well as effects of agency. Hackley and colleagues (2020) evaluated this SPN effect in more detail and in addition assessed possible neural correlates in a parallel fMRI experiment. Acquisition parameters for the fMRI study focused on the level of the insular cortex. Analyses showed that there was greater activation in the anterior insular cortex during the pre-feedback delay in choice than in no-choice trials.

Regarding other brain imaging studies, which did not specifically assess the pre-feedback delay period, one meta-analysis that evaluated the neural correlates of agency looked across 15 different PET and fMRI studies (Sperduti et al., 2011). The meta-analysis distinguished two types of agency: external-agency, which is the attribution of an outcome to something in the environment, outside of one’s control, and self-agency, the attribution of an outcome to one’s own behavior. The latter is the focus of the present study. Sperduti and colleagues found
activations in the bilateral insula, bilateral primary somatosensory cortex, and left premotor cortex that were related to self-agency (2011). They especially emphasized the bilateral insula, which seemed to have a prominent role in the attribution of self-agency. By contrast, external agency was most closely associated with the right angular gyrus.

Another more recent meta-analysis dichotomized agency in a different way (Seghezzi et al., 2019). “Motor intention” refers to a sense of agency for the movement itself. Studies that fit in this category were similar to the Masaki et al. (2010) study in that conditions with choice and no-choice were compared. As these authors used the term, “sense of agency” proper refers to a sense of ownership for the outcome of an action. Studies in this category distorted or delayed visual feedback in certain conditions to alter the feeling of ownership. Motor intention was found to involve activation in regions that included the middle or anterior insula and the pre-supplementary motor area. The most important region associated with sense of agency proper was the temporal-parietal junction of the right hemisphere including, as in the Sperduti et al. (2011) meta-analysis, the right angular gyrus.

**Contextual Valence**

With respect to the feedback receipt, the most important dichotomy is whether this outcome is negative or positive. Very different patterns of brain activity have been observed depending on the valence of outcome (Oldham et al., 2018). With respect to feedback anticipation, it is possible to assess differences by comparing blocks of trials in which rewards are possible but not punishments versus blocks with the reverse. Such a “contextual valence” manipulation has been used in studies of agency. Of particular note was an experiment by Späti and colleagues (2014), that used fMRI to assess the effects of valence and choice when participants were asked to estimate which of two balls would reach a finish line faster (motion
prediction task). After making their selection, a display on the computer screen indicated whether they would win or lose money as a result of their performance at the task, or if the monetary gain or loss was going to occur randomly for that trial. An interaction between agency and valence was found in the right anterior insula; interestingly, greater activation was found for agency trials only in the loss condition. However, this study did not specifically assess activation during the anticipatory interval. We are aware of only two fMRI studies that assessed the pre-feedback interval and included a manipulation of contextual valence, but neither study investigated choice versus no-choice (Andrews et al., 2011; Balodis et al., 2012).

In one of the two EEG experiments that did examine the anticipatory interval, contextual valence and agency interacted. Specifically, the effect of choice versus no-choice on SPN amplitude was limited to the potential gain context in the study by Mei and coauthors (2018). By contrast, in the experiment by Hackley and colleagues (2020) there was an almost significant trend, but it was the opposite of that found by Mei et al. (2018). The more recent study found larger SPN amplitudes in posterior sites in the potential loss context rather than the potential gain context. These apparently inconsistent findings make it clear that more research is needed to better understand the relationship between agency and contextual valence, as well as how valence is represented in the brain.

**Time-Series Analysis and Time-Frequency Analysis**

In the vast majority of the previously mentioned EEG studies examining the sense of agency and the period preceding feedback, a traditional time-series analysis (or event related potential/ERP analysis) was used. An ERP is only produced if hundreds of thousands of neurons are all activated at the same time, in-phase, producing a voltage fluctuation that can be recorded by electrodes on the scalp. Figure 1, for example, shows results from Mei and colleagues (2018),
where the SPN was observably larger in trials when participants believed they had agency (solid lines) versus when they did not (dashed lines), but only on trials with potential gain (blue lines).

**Figure 1**

*Example of Time-Series Analysis Plot*

![Time-series analysis plot](image)

*Note.* Time-series analysis example, taken from Mei et al. (2018) showing SPNs at the F8 electrode site. Blue lines represent gain/nongain trials, whereas red lines represent loss/nonloss trials. Solid lines are choice trials, and dashed lines are no-choice trials. Onset of the feedback display occurred at 0 ms.

As previously summarized, a different pattern of results was obtained in a very similar experiment by Hackley and coauthors (2020, Experiment 1) which, like the Mei et al. (2018) experiment, followed the general methods of Masaki and colleagues (2010). Participants were led to believe that the decision they made during choice trials determined whether they would win or lose 50 yen, but in actuality, outcomes were random on both choice and no-choice trials. As shown in Figure 2, larger SPN amplitudes were observed on choice than no-choice trials, but unlike in Mei et al. (2018), this pattern did not differ significantly between chance-to-win and chance-to-lose trials.
Figure 2

*SPN Amplitudes Differing by Condition*

Note. Grand average ERPs from Hackley et al. (2020). Blue lines represent reward (REW, chance to win) trials, where subjects could win either ¥50 or ¥0; whereas red lines represent punishment (PUN, chance to lose) trials, where subjects could lose either ¥50 or ¥0. Solid lines are choice trials, and dashed lines are no-choice trials.

In the parent study (Hackley et al., 2020), the EEG data were only analyzed in terms of ERPs. One weakness of a time-series analysis concerns phase cancelation. If at one point in time on a given trial there is a voltage of one polarity, but on a subsequent trial the voltage at that instant is of the opposite polarity, the signals will cancel each other out. Consequently, there is considerable overall loss of information in an ERP-style analysis. In contrast, time-frequency analysis does not suffer from the same pitfall, but rather considers these fluctuations as useful parts of the signal that can be analyzed. Random trial-by-trial fluctuations would still be considered noise, but differences in power occurring at consistent points in time and at consistent frequencies may be assessed in time-frequency analysis in a way that is not possible in time-series analysis.

Figure 3 displays an example of a typical time-frequency plot: the x axis symbolizes time (ms), the y axis represents frequency (Hz), and color denotes amplitude (or power, μV²), with red indicating increases relative to baseline, and blue decreases (or suppression). This example was
drawn from Bhangal and colleagues (2021), in which subjects participated in a motor learning task that included delayed feedback. Alpha (8-12 Hz) power was suppressed during the motor response (-8000 to -6000 ms), and then rebounded while the subject was awaiting feedback.

In addition to retaining oscillatory signals that are not in-phase, time-frequency analysis is also superior in that oscillatory signals are segregated according to frequency bands that can have distinct functional correlates. One of the goals of the planned reanalysis for the current study was to reveal new insights into the neural correlates of agency and contextual valence.

**Figure 3**

*Example of Time-Frequency Analysis Plot*

*Note.* Time-frequency analysis example taken from Bhangal et al. (2021). During the time when a subject was making a movement, alpha was suppressed (blue), followed by alpha activation (red) immediately after the cessation of the movement while the subject awaited feedback on their performance. Onset of the feedback display occurred at 0 ms.

**The Current Study**

This was the first study to our knowledge that utilized time-frequency analyses to gain a better understanding of the effect of perceived agency and contextual valence on EEG activity during the pre-feedback delay. To accomplish this, the current study reanalyzed data obtained from Hackley and colleagues (2020, Experiment 1).

In this experiment conducted at Waseda University, subjects participated in a gambling task similar to the one used in Masaki et al. (2010). They selected one of two boxes on choice trials, but on no-choice trials, only a single button was available, which indicated that a computer
would make the decision for them after being pressed (Figure 4). After the response was made, there was a brief delay, followed by feedback on whether money was lost or gained. Unbeknownst to the participants, their sense of agency was merely an illusion, as the computer randomly determined whether they won or lost money in both choice and no-choice trials.

Figure 4

*Trial Structure from Hackley et al. (2020, Experiment 1)*

*a. Reward condition*

Choice trial

No-Choice trial

*b. Punishment condition*

Choice trial

No-Choice trial

Note. Basic trial structure for the REW condition (a) and PUN condition (b). From Hackley et al. (2020). After making a keypress, participants’ responses were denoted by a blue arrow pointing to their selection (in choice trials) or a blue diamond to signify their keypress had been registered (in no-choice trials). A ¥50 Japanese coin (either intact or broken) was used to signify monetary gain or loss, and an empty circle represented an absence of gain or loss. Not shown are examples of the control condition (CON) in which neither gain nor loss was possible, and gray-filled circles were displayed at feedback.
Localization of Agency Effects

There was a second experiment reported by Hackley et al. (2020) that used the same task but recorded brain activity via fMRI rather than EEG. The insula was the region of interest, and when analyzing the pre-feedback delay, the fMRI analysis showed greater activation in the anterior insular cortex during choice trials, especially in the right hemisphere. These results were also reflected in their ERP analyses, as can be seen in topographical plots of SPN amplitudes just prior to receiving feedback (Figure 5a). In studies that focused on the post-feedback interval, it was already well-established that this area is involved in the sense of agency (Seghezzi et al., 2019; Sperduti et al., 2011). Additionally, in one paper that studied oscillatory power as it related to the modulation of self agency, it was suggested that alpha is the main neural oscillation pertaining to this construct, as alpha suppression seeming to originate in or near the insula increased as a sense of self agency increased (Kang et al., 2015). Thus, we anticipated that in the time period when a subject is awaiting feedback, there would be a suppression of alpha, which is an indicator of cortical activation, arising from electrode sites overlying the right anterior insula during choice trials.

Beta suppression has also been closely associated with modulations in self agency, albeit not to as large of a degree as alpha suppression (Kang et al., 2015). Therefore, we also expected beta (13-30 Hz) suppression emanating from sites overlying the supplementary motor area (Pfurtscheller et al., 1997) prior to feedback, as that was an important area in a meta-analysis that used fMRI to assess choice vs no-choice studies (Seghezzi et al., 2019).

Contextual Valence

Additionally, we wanted to investigate whether there would be any variation in brain activation depending on contextual valence condition (reward versus punishment, or REW
versus PUN). The ERP analyses in the original study (Hackley et al., 2020) found an almost significant trend towards larger amplitudes in posterior sites in the PUN condition, however, the current literature contains many conflicting results. An experiment by Chen and colleagues (2018) looked at SPN effects at different levels of reward probability and how this interacted with perceived agency. They reported a significantly larger SPN in the choice condition when the probability of reward was high (75%) and medium (50%), but not when reward probability was low (25%). Additionally, in an fMRI study assessing differences in brain activity in potential gain versus potential loss contexts, researchers noted increased activity in the ventral striatum in choice as compared to no-choice trials when there was a potential gain, but found no significant difference between choice and no-choice in potential loss trials (Leotti & Delgado, 2014).

The null results obtained by Hackley and colleagues (2020) are consistent with null findings for contextual valence during anticipation of emotion-inducing photographs. For example, in a paper by Sabatinelli, Bradley, and Lang (2001), heterosexual young men with a phobia of snakes were exposed to images of snakes, ordinary household objects, or attractive female nudes. They found that while the arousal of the men appeared to be altered depending on expected slide category, their emotional valence (as assessed with startle-blink probes) did not differ significantly between trials in which snakes and nudes were anticipated. Since the anticipation of motivationally relevant stimuli was insensitive to valence in this startle-blink study, which used a very strong manipulation of emotion, it follows that enhanced insular cortex activity during the pre-feedback delay period would not differ between the REW and PUN conditions. Consequently, we expected that the null hypothesis would be supported for this particular analysis.
Visual Attention

I also examined a surprising finding from the original study: during control (CON) trials, visual cortex activity appeared to be just as high as it was during both the reward and punishment trials (Figure 5b). This was unexpected, as there was no possibility of monetary gain or loss during these trials, and the feedback display looked identical on every trial. It is well established that SPN amplitude and topography are sensitive to anticipatory attention. For example, when the SPN was compared across conditions with different feedback modalities, amplitudes were largest over the occipital region for visual feedback, but over frontocentral sites for auditory feedback (Brunia & Van Boxtel, 2004). In a similar vein, when Kotani and colleagues (2003) compared participants’ SPNs in conditions with highly specific feedback versus a simple binary “correct” or “incorrect” outcome, SPN amplitude was larger in the high information condition. Given that feedback displays in the CON condition from the study by Hackley and collaborators conveyed no useful information, it seems odd that there was no obvious reduction of visual cortex activity in their fMRI experiment or of posterior SPN amplitude in their EEG experiment.
In a variety of previous studies of delayed feedback looking at both visual and auditory modalities, topographically specific alpha (8-12 Hz) suppression has been observed prior to receiving feedback (Bastiaansen et al., 2002; Bastiaansen & Brunia, 2001). Based on these previous findings in the literature, it is possible that the apparent lack of differences in visual cortex activity across contextual valence conditions reflects insensitivity of the methods used. If so, a reanalysis using time-frequency methods might reveal greater suppression of alpha at occipito-parietal sites in the experimental conditions (REW and PUN) than the CON condition in the period prior to feedback.

**METHOD**

**Participants**

Thirty-two undergraduate and graduate students were recruited for this experiment, five of whose data were later removed due to technical issues in their EEG recordings, and one who was removed from the study due to a lack of complete behavioral data. Of the twenty-six remaining, 14 were male and 12 were female, with ages ranging from 19-34 ($M \pm SD: 21.0 \pm 1.2$ y). Two out of the 26 participants were left-handed. This study was approved by the Waseda University ethics committee, and informed, written consent was obtained from all participants.

**Procedure**

In order to compare potential gain versus loss contexts, there were two conditions: reward (REW), in which participants could either gain ¥50 or ¥0, and punishment (PUN), in which participants could either lose ¥50 or ¥0. There was also a control condition (CON) in which no money could be won or lost and no useful feedback was provided.

At the beginning of the gambling task, participants were given ¥2,000 (US equivalent ~ $17) as their base allotment. At the conclusion of the experiment, all net winnings were paid out,
and all net losses were forgiven, with a final payment average of ¥2,419 across participants. No participant received a final amount lower than ¥2,400 (¥800/hr for 3 hours of service). The nature of the gambling task (except that net losses would be forgiven) was explained to participants prior to asking for consent.

The basic trial structure progressed as follows: first, a fixation cross was presented on the screen for 500 ms, after which two empty boxes appeared on each side of the cross. The empty boxes were displayed for 500 ms, and then were filled with either question marks, which signified a choice task, or exclamation marks, which signified a no-choice task. In the no-choice task, participants simply used their right thumb to press a button on the provided response box. When presented with the choice task, participants had the option to press the first or second finger key with their right hand to make a selection. Once participants responded with their choice, the fixation cross was replaced with a blue arrow which pointed to whichever option they had selected. During no-choice trials, a blue diamond replaced the fixation cross to simply demonstrate that the thumb-press response had been registered.

In both trial types, feedback was displayed on the screen 2.5 seconds after the button-press had been registered. In the REW condition, monetary gain was represented by an intact ¥50 coin, whereas in the PUN condition, a broken ¥50 coin was displayed to signify monetary loss. In both conditions, an empty circle that was the same diameter as the coin was used to signify no gain (in the REW condition) or no loss (in the PUN condition). Despite the fact that it was implied that participants’ actions affected their outcomes in choice trials, favorable and unfavorable outcomes were determined randomly, and had an equal chance of occurring. Just as in the two previously mentioned studies which utilized this gambling task (Masaki et al., 2010; Mei et al., 2018), the goal was to create the illusion of agency in choice trials for the participants.
For feedback in the CON condition, instead of broken or solid coins, gray-filled circles displayed inside of both boxes. This condition was created so that any movement-related potentials produced that could potentially overlap the SPN could be estimated, among other things.

Each trial block began with a display that indicated the experimental condition. The CON condition had 16 trials per block, and the REW and PUN conditions were composed of 64 trials per block. There were an equal number of choice and no-choice trials (randomly selected), and as mentioned previously, there was an equal chance of experiencing a better or worse outcome (potential gain versus no gain in REW blocks and potential loss versus no loss in PUN blocks) regardless of participants’ selections. Half of the participants experienced the three conditions in the order C-R-C-P-C-R-C-P-C and the other half experienced the three conditions in the order C-P-C-R-C-P-C-R-C. Prior to beginning the nine experimental blocks, participants could practice the CON condition as many times as they needed until they felt comfortable with the experimental procedure. The inter-trial interval was 1,600 ms.

**Questionnaire**

After completing the EEG experiment, participants responded to a questionnaire which asked questions about choice and no-choice trials in the three valence conditions. Participants used a 7-point scale to rate how much control they felt they had regarding whether they won or lost money, which of the two cues (\(?+?\) or \(!+!\); choice or no-choice, respectively) was more attention-grabbing for them, and how confident they were in being able to discern a pattern in the correct options.
EEG Acquisition and Processing

Participants were seated about 1.2 m from a computer in an electrically shielded, sound-attenuated chamber. EEG was recorded at 128 sites using Ag/AgCl electrodes; horizontal and bipolar EOGs were also acquired so that the data could be corrected for blinking and other ocular artifacts. A Biosemi Active Two system (Biosemi, Inc) was used to record both EEG and EOG with a bandwidth of DC to 102 Hz (roll-off: 3dB/octave) and a sampling rate of 512 Hz.

All of the EEG data was completely reanalyzed subsequent to the analysis and publication of Hackley et al. (2020); this included all preprocessing steps. All EEG preprocessing and analyses were completed using the EEGLAB toolbox (v2020.0, Martínez-Cancino et al., 2020) in MATLAB 2020a (MathWorks, US). EEG was re-referenced to the average voltage of all electrodes, and EEG epochs of 4,500 ms which were time-locked to the onset of feedback were extracted (extending from 3,500 ms before feedback onset until 1,000 ms after feedback onset). After dividing the data into epochs, independent component analysis (ICA) was used to correct ocular artifacts by estimating the activity caused by eye movements or blink artifacts, and removing them (Delorme & Makeig, 2004). EEG epochs that did not exceed ± 150 μV at any point were averaged using the onset of feedback as the time-locking point. The baseline was defined as the mean amplitudes between -3,500 and -2,700 ms preceding feedback onset.

Data Analysis

The original study that collected these data (Hackley et al., 2020) used conventional time-series ERP analyses on the EEG data. In this study, we used a more powerful approach to re-analyze the data: time-frequency analysis, which allowed the extraction of frequency in addition to timing information. These hypothesis-driven analyses were assessed with a 4-way analysis of
variability (ANOVA) over mean values measured in temporospatial regions of interest (e.g., 8 to 12 Hz x -200 to 0 ms, to assess alpha just before feedback). These analyses followed the same structure as the one used in Hackley et al. (2020), with factors of agency (choice/no-choice), contextual valence (REW/PUN), hemisphere (right/left), and caudality (frontal/central/parietal/occipital). All time-frequency plots were thresholded at \( p < .05 \), with non-significant points designated by green pixels. Prior to analysis, the control condition (CON) was subtracted. When done this way, movement-related activity from the early part of the delay interval could be eliminated, as well as other anticipatory effects in the late portion of the delay that were not specifically feedback-related. An overview of statistical results completed without this subtraction of the control condition can be found in the Appendix.

**RESULTS**

**Behavior**

The parent paper (Hackley et al., 2020) of the present study analyzed behavioral measures of participants in the EEG experiment by means of 2 x 2 analyses of variance (ANOVAs) with factors of agency (choice/no-choice) and valence (REW/PUN). Response times (RT) were longer on choice than no-choice trials \( F(1, 26) = 24.35, p < .001, \eta^2_p = 0.48 \), which aligns with what we would expect if the illusion of agency was successfully produced in participants. Contextual valence condition did not have any effect on RT, however, nor was there an interaction between agency and contextual valence on RT \( F(1, 26) < 1, p = 0.59, \eta^2_p = 0.01 \), and \( F(1, 26) < 1, p = 0.85, \eta^2_p < 0.01 \), respectively).

In the questionnaire, participants responded that cues for the choice condition (\(?+\)) engaged their attention more than cues for the no-choice condition (\(!+!\)). In the REW condition, eighteen participants claimed they paid greater attention to choice than no-choice cues, while
five reported the reverse (binomial test, $p = 0.011$). Similarly, in the PUN condition, nineteen participants reported that they paid greater attention to choice than no-choice cues, while three reported the reverse ($p = 0.001$). These numeric ratings on the 7-point scale did not differ significantly between the REW and PUN conditions ($M \pm SD = 2.70 \pm 1.75$, and $2.56 \pm 1.53$, respectively; $t(26) = 0.49$, $p = 0.63$).

Participants reported greater confidence in their ability to detect a pattern in response outcomes during choice than no-choice trials ($F(1, 26) = 17.5$, $p < 0.001$, $\eta^2_p = 0.40$) even though any perception of this nature would have been an illusion. As was the case with RT, there was no main effect of valence, nor an interaction effect between valence and agency ($F(1, 26) < 1$, $p = 0.47$, $\eta^2_p = 0.02$, and $F(1, 26) < 1$, $p = 0.31$, $\eta^2_p = 0.04$, respectively).

Curiously, even though all previous behavioral measures had significant main effects of agency, ratings for perceived sense of control on the questionnaire were not significant ($F(1, 26) < 1$, $p = 0.90$, $\eta^2_p < 0.01$). However, there was a significant interaction effect between agency and valence in this measure--there was greater perceived control on choice than no-choice trials in the REW condition, and the opposite was the case in the PUN condition ($F(1, 26) = 4.33$, $p = 0.047$, $\eta^2_p = 0.14$). No main effect of valence was observed ($F(1, 26) < 1$, $p = 0.68$, $\eta^2_p = 0.01$).

It is also worth noting that the analyses of behavioral data from the fMRI portion of the study (Experiment 2) did find main effects of agency; participants rated their sense of control as higher on choice than no-choice trials ($F(1, 25) = 5.31$, $p = 0.030$, $\eta^2_p = 0.18$).

**Time-Frequency Analysis**

In order to assess effects across a variety of hypotheses, time-frequency plots were produced such as the one below (Figure 6), which has columns for choice and no-choice, and rows to assess the contextual valence conditions: reward, punishment, and control. In each plot,
time in milliseconds (ms) was graphed on the x axis, and frequency in Hertz (Hz) was graphed on the y axis. The event marker at -2,500 ms indicates the point at which a participant made a keypress response, and the marker at 0 ms is when feedback about the outcome of the trial was received. For all time-frequency plots, orange regions indicate an increase in power relative to baseline, and blue regions indicate a decrease in power relative to baseline. Green regions indicate no significance. In Figure 6, which is an average across all electrode sites, blue and orange regions in the alpha and beta bands are indicative of the suppression of activity while a participant made a movement (-3,000 to -2,000 ms) followed by a rebound of mu (alpha) activity during the pre-feedback delay period (-2,000 to 0 ms). The control condition has not been subtracted from the data shown in this figure.

These findings were expected, as they are well-known effects which have been consistently produced in previous research in motor electrophysiology (Pfurtscheller & Lopes Da Silva, 1999). Theta power (3-7 Hz) occurring after feedback (100 to 500 ms) was observed in the REW and PUN conditions during choice trials. This theta activity may be indicative of the feedback-related negativity (FRN), which typically occurs during reward-based learning after feedback when the outcome is worse than expected (Cavanagh & Frank, 2014; Crowley, 2013; Rawls et al., 2020).
Figure 6

Average of Activity Across All Electrodes

Note. Example of one of the time-frequency analyses that was conducted using all electrodes. From top to bottom, rows are the contextual valence conditions (reward, punishment, and control) and from left to right, columns are the agency conditions (choice and no-choice).

Pre-feedback Alpha Activity

After reviewing activity that was consistent across all electrodes, further time-frequency analyses were completed at different electrode sites relevant to our hypotheses to assess effects of agency, contextual valence, and visual attention. We were particularly interested in oscillations occurring just prior to receiving feedback. As noted previously, activity in the corresponding control condition was subtracted to isolate processes specific to feedback anticipation. In the figures that follow, green indicates that the difference relative to control trials is not greater than during the baseline interval.

Within this pre-feedback period, alpha suppression appeared to be greatest over occipital and right frontal sites. Figure 7 shows both a topographical plot of distribution of activity in the
alpha band, as well as a time-frequency analysis of activity at right frontal electrodes (F4 and F8) across several frequency bands. Alpha suppression appeared to be more salient during reward choice trials prior to feedback in right frontal areas, but this impression of regional specificity was not confirmed statistically.

Figure 7

Pre-feedback Alpha Activity: Agency and Contextual Valence

Note. The topographical plots (a) were created by averaging activity occurring prior to feedback (-50 to 0 ms) in the alpha band (11 Hz). Rows are choice, no-choice, and choice – no-choice, and columns are PUN – CON, REW – CON, and the difference between the first two columns. The subsequent time-frequency figure (b) shows activity across a variety of frequency bands at sites overlying the right anterior insula (F4 and F8). Similar to the topographical plots, rows are choice – no-choice, and columns are REW – CON and PUN – CON.

To assess visual attention, we focused on electrodes overlying the occipital cortex (Figure 8). Time-frequency analyses revealed an effect for both the punishment and reward conditions.
during choice trials. Although alpha suppression was present during punishment choice trials, it appeared to be more prominent during choice trials in the reward condition. This interaction of agency and contextual valence was documented by the 4-way ANOVA of average power within the final 200 ms of the delay \( F(1, 25) = 7.16, p = 0.013, \eta_p^2 = 0.22 \). Alpha suppression during choice trials was limited to the reward condition (top row of Figure 7b) (\( t(25) = 2.374 \), FDR-corrected \( p = 0.026 \)).

Agency also interacted significantly with caudality \( F(3, 75) = 4.66, p = 0.005, \eta_p^2 = 0.16 \). The greater alpha suppression on choice trials was absent at sites overlying sensorimotor cortex (C3, C4), presumably because the effect was eclipsed by mu/alpha rebound (Figure 6).

**Figure 8**

*Pre-feedback Alpha Activity: Visual Attention*

![Pre-feedback Alpha Activity: Visual Attention](image)
*Note.* The topographical plots (a) were created by averaging activity occurring prior to feedback (-50 to 0 ms) in the alpha band (11 Hz). The time-frequency figure (b) shows activity across a variety of frequency bands at occipital sites (O1, Oz, and O2).

**Pre-feedback Beta Activity**

Pre-feedback beta suppression also varied as a function of agency and contextual valence. Beta suppression appeared to be strongest at left frontal sites (Figure 9). Similar to the pre-feedback alpha finding, the reduction in beta power was most evident during choice trials in the reward condition. In the analysis of mean amplitude in the period prior to feedback (-200 to 0 ms), valence interacted significantly with caudality and also with hemisphere ($F(3, 75) = 3.16, p = 0.030, \eta^2_p = 0.11$, and $F(1, 25) = 6.37, p = 0.018, \eta^2_p = 0.20$, respectively). Less power was observed in the reward than punishment condition, but this effect was reduced or even reversed at sites near the hand area of sensorimotor cortex in the left hemisphere (see right column of Figure 9a). This pattern might indicate oscillatory rebound within cortical regions in which beta activity had been suppressed during the right-hand keypress response.

Agency interacted significantly with both caudality ($F(3, 75) = 3.75, p = 0.014, \eta^2_p = 0.13$) and valence ($F(1, 25) = 10.56, p = 0.003, \eta^2_p = 0.30$). Mean amplitudes were significantly lower in choice as compared to no-choice trials at occipital sites ($t (25) = 2.76$, FDR-corrected $p = 0.011$). Additionally, beta suppression was significantly greater in the reward condition than the punishment condition, but only during choice trials ($t (25) = 2.93$, FDR-corrected $p = 0.007$).
Figure 9

*Pre-feedback Beta Activity: Agency and Contextual Valence*

**Note.** The topographical plots (a) were created by averaging activity occurring prior to feedback (-50 to 0 ms) in the beta band (17 Hz). The time-frequency figure (b) shows activity across a variety of frequency bands at left frontal sites (F3 and F7).

**DISCUSSION**

The purpose of this experiment was to study the effects of agency and contextual valence on brain activity prior to feedback using time-frequency analysis, which is a more powerful method than the ERP analyses done by the parent study. The two major findings were pre-feedback alpha suppression that was greatest in reward choice trials over occipital and right frontal sites and pre-feedback beta suppression that was greatest in reward choice trials over left frontal sites.
The frontal alpha suppression we found prior to feedback is one that was anticipated based on the results of several previous studies. While there have been several brain areas identified as being involved in a sense of agency, one of the most recurring regions is the bilateral insulae (Hackley et al., 2020; Seghezzi et al., 2019; Sperduti et al., 2011). Given that the suppression of alpha activity is an indicator of cortical activation, we expected that we would observe increased alpha suppression prior to feedback in the choice condition; this was supported by our analyses. Surprisingly, while we predicted that contextual valence would have no effect on pre-feedback alpha suppression, there was an interaction effect between agency and contextual valence: alpha suppression prior to feedback was significantly greater in reward choice trials. In the previously published analyses from these data (Hackley et al., 2020), SPN amplitude was significantly greater in choice trials in sites in the right hemisphere. Our analysis noted only a slight, non-significant preponderance of alpha suppression for the right hemisphere.

In addition to frontal alpha suppression prior to feedback, we also found increased pre-feedback alpha suppression originating from occipital sites. This activity was greatest during reward choice trials, and discernable to a slightly lesser degree during punishment choice trials. Alpha suppression prior to receiving feedback has been observed in a variety of studies (Bastiaansen et al., 2002; Bastiaansen & Brunia, 2001), and many previous papers have demonstrated differences in neural activity when participants were given useful feedback versus feedback that was irrelevant (Kotani et al., 2003; Walentowska et al., 2018). During the control condition of this study, participants were aware that it was impossible to win or lose money, and thus that the display they were shown in lieu of feedback contained no relevant information. We hypothesized that we would observe greater alpha suppression in sites overlying occipital cortex prior to valenced feedback as compared with control. This was supported by our analyses,
though a difference between reward and punishment versus control was only present during choice trials. This finding conforms to our assumption about brain activity for relevant versus irrelevant information, since feedback on no-choice trials would also not be considered useful for the participants.

The literature on beta suppression is not as extensive as for alpha suppression, but a handful of studies had previously identified beta suppression as also being relevant in studies of agency (Kang et al., 2015; Pfurtscheller et al., 1997). In one meta-analysis that used fMRI rather than EEG methods to assess choice versus no-choice differences, authors found that the pre-SMA was highly active during conditions of motor control, the type of agency relevant to the present study (Seghezzi et al., 2019). We hypothesized that we would observe greater beta suppression prior to feedback in electrode sites overlying the pre-SMA during choice trials. Like our prediction pertaining to alpha suppression, we anticipated no differences based on contextual valence. Analyses revealed an interaction of agency and contextual valence: there was greater pre-feedback beta suppression during reward choice trials. However, activity appeared to be originating not from the pre-SMA, but from left frontal sites. A more likely neuroanatomical origin is suggested by data from the fMRI portion of the study by Hackley and colleagues (2020, Experiment 2). One of the handful of areas that was activated differentially as a function of choice versus no-choice was a region in the ventrolateral prefrontal cortex (PFC) on the left hemisphere, the pars triangularis (BA 45). A different recently published study of reward anticipation (but not of agency) also found pre-feedback beta modulation in the same left frontal area as we did (Coffman et al., 2021). However, while their effect did vary with contextual valence, there was greater beta suppression in the punishment condition than the reward condition.
As has been mentioned, it is interesting that for all of our findings relating to alpha and beta suppression, activity appeared to be stronger for reward versus control than punishment versus control. This was a somewhat unanticipated finding, as a great many previous psychological studies have provided evidence for a “loss aversion,” or greater psychological and neural sensitivity to loss versus gain (Brenner et al., 2007; Kahneman & Tversky, 1982; Sokol-Hessner & Rutledge, 2019). However, the impact of losses and gains may not have been precisely balanced in our study. In our gambling task, participants had a chance to win ¥0 or ¥50 in the reward condition or a chance to lose ¥0 or ¥50 in the punishment condition. At the end of the experiment, participants were allowed to keep all of their winnings, but net losses were forgiven. While the fact that losses would be forgiven was not revealed to participants when the task was explained to them, it is possible that they may have guessed that this would be the case. If so, this might be a possibility as to why the results comparing the punishment versus control conditions were not as salient as those comparing reward versus control.

An alternative explanation may be that, in studies of attribution, most people have a tendency to attribute positive outcomes to themselves, but negative outcomes to external sources (Brewin & Shapiro, 1984; Rotter, 1966). Therefore, it could be the case that participants had a much greater sense of agency in the reward condition than the punishment condition, where they may have instead attributed their outcomes externally. Our post-experimental questionnaire results are consistent with this assumption.

It is also possible that existing EEG measures (e.g., SPN, Reward Positivity/RewP, alpha suppression) are more sensitive to parts of the reward system that process positive outcomes than those concerned with the avoidance of negative outcomes. In any case, among other studies comparing neural activity in gain versus loss contexts, findings have been conflicting. The
previous ERP analyses of these data (Hackley et al., 2020) observed a trend toward greater choice versus no-choice differences in loss as compared to gain contexts. However, a different experiment by Mei and colleagues (2018), which used very similar methods, found results reminiscent of our present analyses. Differences in SPN amplitude between choice and no-choice conditions was larger in potential gain than potential loss contexts.

This study supports previous research regarding the relevancy of a sense of agency, and provides evidence that the particular valence of the anticipated outcome (potential gain versus potential loss) has an impact on the processing of relevant neural activity. Outcomes for which we are not the agent (as in the no-choice trials) or which do not provide task-relevant feedback (as in the control condition) elicit little anticipatory attention. This study also extends previous work on which brain areas may be involved in these processes. It furthermore demonstrates that time-frequency analysis as a means of analyzing EEG data can be a valuable tool in revealing insights that might not be apparent in more traditional ERP style analyses.
REFERENCES


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APPENDIX

Analysis Without Subtraction of Control Condition

This appendix contains a breakdown of our statistical findings for the data when there is no subtraction of the control condition. Just like those presented in our results section, we assessed these effects using a 4-way ANOVA with factors of agency (choice/no-choice), contextual valence (REW/PUN), hemisphere (right/left), and caudality (frontal/central/parietal/occipital). The pre-feedback period used for analysis was defined as -200 to 0 ms. Significant results from our omnibus ANOVA were followed up with pairwise t tests.

When assessing pre-feedback alpha activity there was a significant main effect of caudality ($F(3, 75) = 4.79, p = 0.004, \eta^2_p = 0.16$) as well as a significant interaction between caudality and agency ($F(3, 75) = 5.10, p = 0.003, \eta^2_p = 0.17$). Mean alpha amplitude was significantly lower when comparing frontal sites with parietal sites ($t(25) = -4.67, \text{FDR-corrected } p = 0.001$) and occipital sites with parietal sites ($t(25) = -3.44, \text{FDR-corrected } p = 0.006$). Alpha amplitude was significantly lower in choice than no-choice trials in frontal, parietal, and occipital areas ($t(25) = -2.32, \text{FDR-corrected } p = 0.029$, $t(25) = -2.17, \text{FDR-corrected } p = 0.040$, and $t(25) = -3.16, \text{FDR-corrected } p = 0.004$, respectively). Additionally, a significant interaction between valence and agency was also found ($F(1, 25) = 7.16, p = 0.013, \eta^2_p = 0.22$). Alpha suppression during choice trials was limited to the reward condition ($t(25) = 2.37, \text{FDR-corrected } p = 0.026$).

Analyses of pre-feedback beta activity revealed significant main effects of caudality ($F(3, 75) = 5.39, p = 0.002, \eta^2_p = 0.18$) and agency ($F(1, 25) = 8.18, p = 0.008, \eta^2_p = 0.25$). Mean amplitudes were significantly lower in frontal compared to parietal sites ($t(25) = -3.47, \text{FDR-}$
corrected $p = 0.007$) and occipital compared to parietal sites ($t(25) = -3.38$, FDR-corrected $p = 0.007$). Amplitudes were also significantly lower in choice than no-choice trials ($t(25) = -2.86$, FDR-corrected $p = 0.008$). Agency interacted significantly with caudality and contextual valence ($F(3, 75) = 4.48, p = 0.006, \eta^2_p = 0.15$, and $F(1, 25) = 10.56, p = 0.003, \eta^2_p = 0.30$, respectively). Beta suppression was greater in choice versus no-choice in frontal, parietal, and occipital sites ($t(25) = -2.96$, FDR-corrected $p = 0.007$, $t(25) = -3.47$, FDR-corrected $p = 0.002$, and $t(25) = -4.28$, FDR-corrected $p < 0.001$, respectively). Mean beta amplitudes were lowest during reward choice trials ($t(25) = 2.93$, FDR-corrected $p = 0.007$).