The Electrophysiology of Cognitive Dissonance-elicited Attitude Change

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Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

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Abstract

Despite the influence that cognitive dissonance theory has had in psychology over the last sixty years, its neural correlates have only recently been investigated. The current study used electroencephalography (EEG) to explore cognitive dissonance-elicited attitude change in a free-choice paradigm. Event-related potentials (ERPs) time-locked to stimulus onset found greater voltage negativity over centro-parietal scalp during re-evaluation of dissonant choice items relative to consonant choice items, and greater negativity over left lateral anterior scalp during trials containing dissonance-reducing attitude change relative to trials without. Left lateral anterior scalp voltage amplitude was found to be negatively correlated with the magnitude of resulting attitude change. A time-frequency analysis revealed effects for high and low alpha and theta frequencies. These finding are consistent with a model of cognitive dissonance in which cortical projections of ventral striatal activity reflect reward signal changes, and where left prefrontal cortex is recruited for cognitive control and emotional down-regulation.

Keywords: cognitive dissonance; attitude change; event-related potentials; time-frequency analysis

Dedication

To Jen, Jeff, and Sarah.

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Chapter 1. Introduction

In the dystopian novel *Nineteen Eighty-Four*, George Orwell (1949) coined the term “doublethink”, a voluntary mental contortion practised by members of the authoritarian Party. “Doublethink”, Orwell explained, “means the power of holding two contradictory beliefs in one’s mind simultaneously, and accepting both of them”. As most people can attest, coming to the realization that one's beliefs form a contradiction with each other results in an uncomfortable emotional state. Contemporary readers' intimate acquaintance with this experience quickly helped usher Orwell's term into common English parlance.

A few years after *Nineteen Eighty-Four*'s publication, the social psychologist Leon Festinger wrote on what would become one of the most studied psychological phenomena and most successful theories in all of psychology (Festinger, 1956). Festinger's *When Prophecy Fails* provided an account of a doomsday cult's end-times predictions, and documented the cultists' subsequent bizarre rationalizations when these predictions failed to come to pass. While embedded in the cult, Festinger observed that the cultists, when faced with the fact that they had erred in their end-of-the-world prognostication, chose to become even more fervent in their beliefs, spinning the failure as a sign that their devotion had convinced God to spare humanity. Festinger explained this behaviour through a new psychological theory which he called “cognitive dissonance theory” (Festinger, 1957). The theory proposed that when two or more logically-entangled but contradictory beliefs come head-to-head, an unpleasant feeling of “dissonance” is experienced in the belief-holder that demands resolution. With cognitive dissonance theory, Festinger had identified the psychological phenomenon that had a few years prior made Orwell's doublethink resonate with the public. Whereas doublethink referred to the *ability* to hold two contradictory beliefs in one’s mind simultaneously, cognitive dissonance referred to the *discomfort* that was aroused by doing so[1], and where doublethink required the *acceptance* of these contradictory beliefs, cognitive dissonance more naturally inspired the *rejection* (or alteration) of at least one of them, done so in order to free oneself of the discomfort they evoke and to restore mental consonance. In Orwell's dystopian world, doublethink was only possible in the absence of or in a complete triumph over cognitive dissonance.

According to the theory, cognitive dissonance arises when two or more conscious beliefs conflict; therefore, in order to escape dissonance when a contradiction is encountered, something about an individual's set of beliefs must change. There are a number of changes that can be made to reduce the level of dissonance one experiences: more consonant beliefs can be introduced to one's belief set, or the number of dissonant beliefs can be reduced, or the importance assigned to the consonant beliefs can be increased, or the importance assigned to the dissonant beliefs can be decreased (Festinger, 1957, as cited in Frey et al., 1982). Not all beliefs are equal, however, as some beliefs are more amenable to change that others, and accuracy of a belief is routinely compromised in order to accommodate the beliefs which are the least malleable. An individual's recent behaviours therefore have a powerful influence on the determination of how and which beliefs will be altered, as the beliefs that are usually the most resistant to change are beliefs pertaining to actions which have undeniably been performed and which cannot be undone.

Since first being described, the theory of cognitive dissonance has endured many attempts at disconfirmation and appeals to alternative explanations, though ultimately the theory has stood up against this scrutiny and finer analysis (Harmon-Jones & Harmon-Jones, 2007). Measurements of skin conductance during a cognitive dissonance-eliciting task showed that cognitive dissonance arouses the sympathetic nervous system and therefore can be physiologically detected (Harmon-Jones, Brehm, Greenberg, Simon, & Nelson, 1996). The phenomenon has further been confirmed by investigations of HPA-axis activity, which reveal a connection between

1 “dissonance” referring to both the discomfort and to the disharmonious state of contradictory beliefs itself.

cognitive dissonance reduction and a decline in salivatory cortisol (Kimel, Lopez-Duran, & Kitayama, 2015). When researchers attempted to elicit cognitive dissonance in participants by instructing them to lie, dissonance was predictably absent in those individuals who scored high in psychopathic traits (Murray, Wood, & Lilienfeld, 2012).

1.1. Cognitive Dissonance-elicited Attitude Change

As mentioned, beliefs do not need to be abandoned in their entirety in order to restore consonance. Instead, the strength or importance of beliefs can be modified to accommodate a stronger or more valued belief that is therefore more resistant to alteration. Attitudes or preferences are quite amenable to this sort of change, and a number of paradigms have been designed that elicit attitude change and are powered by the drive for dissonance resolution. In a classic experiment using an "induced compliance" paradigm, Festinger and Carlsmith (1959) paid participants either 1 or 20 dollars to engage in a boring, unpleasant task. Critically, the experimenters also requested that after the task each participant would reassure the participant coming in after that the task was interesting. Afterwards, when asked how interesting the task was, participants who were paid one dollar to complete the task rated the experiment as being much more interesting than those who were paid 20 dollars. Cognitive dissonance theory explains these results by suggesting that the higher payment of 20 dollars was sufficient compensation for the participants to justify lying to other participants about the boring task, while the meagre one dollar compensation was not. The resulting "I lied for no justifiable reason" dissonance was reduced by reducing the magnitude of the lie that the participant told, which they accomplished by *changing their own attitude* about the interestingness of the task in a positive direction (participants did not convince themselves that the task was *pleasant*, but merely that it was not as bad as they had originally assessed it be).

Another commonly used attitude change paradigm is the "free-choice" paradigm, first pioneered by Brehm (1956). In this paradigm, participants are instructed to make a binary choice between pairs of items, where one item is selected and the other is rejected. When the items are disparate in their subjective value to the participant, with one item clearly more preferred than the other, the choice is easy and the decision to pick one over the other arouses no dissonance. However, when both items are very similar in their desirability and the participant must nevertheless make a choice between them, the act of choosing produces a dissonance-inducing contradiction, either “I rejected an item I like” or “I selected and item I dislike”. According to cognitive dissonance theory, any favourable beliefs about a rejected item or unfavourable beliefs about a selected item will become dissonant; therefore, in order to resolve this dissonance, participants must alter their subsequent evaluations of the pair of items so that the reject item is valued less than the selected item. This can be accomplished by either changing one's attitude toward the rejected item to make it more negative, or by changing one's attitude toward the selected item to make it more positive, retroactively turning what was a difficult choice between two similar item into an easier choice between two slightly more disparate options (In the absence of dissonance, attitudes are not expected to change significantly between pre- and post-choice evaluation). Numerous studies have succeeded in inducing attitude change using the free-choice design, and have done so with variety of stimuli such as home appliances (Brehm, 1956), imagined vacations (Sharot, De Martino, & Dolan, 2009), food (Izuma, Matsumoto, Murayama, Samejima, Sadato, & Matsumoto, 2010), paintings and baby names (Jarcho, Berkman, & Lieberman, 2011), and music (Qin, Kimel, Kitayama, Wang, Yang, Han, 2011; Kitayama, Chua, Tompson, & Han, 2013).

1.2. The Neural Bases of Cognitive Dissonance and Attitude Change

Early behavioural research into cognitive dissonance and attitude change stirred questions about their underlying neural mechanisms. The use of neuroimaging techniques in conjunction with the aforementioned attitude change paradigms has resulted in a number of candidate neural structures and processes proposed to be responsible for cognitive dissonance's behavioural and affective effects. Among studies that employed a free-choice paradigm, the anterior cingulate cortex (ACC) is identified as playing a role in the dissonant choice phase (Van Veen, Krug, Schooler, & Carter, 2009; Izuma et al., 2010; Kitayama et al., 2013; de Vries, Byrne, Kehoe, 2015), while prefrontal cortices have been thought to be involved in the post-choice attitude change phase (Izuma et al, 2009; Jarcho et al., 2011; Qin, 2011; Kitayama et al., 2013). The ACC has been associated with negative affect (Price, 2000; Ochsner & Gross, 2005), and event-related potential (ERP) studies of the error-related negativity (ERN) have shown that the ACC is involved with the detection of higher-order conflict (Carter & van Veen, 2007), even for higher-order conflicts such as that between behaviour and self-concept (Amodio et al., 2004). The activation of ACC and DLPFC during cognitive dissonance would support the interpretation of the ACC as a cognitive conflict detector, which then recruits dorsolateral prefrontal cortex (DLPFC) to respond to the detected conflict (Carter, Braver, Barch, Botvinick, Noll, & Cohen, 1998; Gehring, Gross, Coles, Meyer, & Donchin, 1993; Carter & van Veen, 2007).

The neural mechanisms for attitude change were investigated by Sharot et al. (2009) in a functional neuroimaging study which concluded that the decision-phase of a free-choice paradigm alters the hedonic value of the presented items. When comparing activity during pre-choice and post-choice rating phases, Sharot et al. found that blood-oxygen-level dependent (BOLD) signals in caudate nucleus matched changes in participants' stimuli rating behaviour and could predict participants' post-choice ratings. Caudate nucleus may be part of a neural circuit for the representation of hedonic value, with a critical role in reward processes (Delgado, 2007) and assessment (Delagado, Locke, Stenger, & Fiez, 2003), suggesting that attitude change may in some cases operate in part through a change in the representation of a stimuli's hedonic value rather than through changes in emotional response. These findings suggest that rather than a slow, deliberate, conscious change in attitude, dissonance-elicited attitude change may be a rapid, reflexive, unconscious process. This is consistent with findings that cognitive dissonance is present in subjects not thought to be capable of deep, reflective cognition, such in patients suffering from amnesia (Lieberman, Ochsner, Gilbert, & Schacter, 2001), as well as in children and monkeys (Egan, Santos, & Bloom, 2007). However, a study by Martinie, Olive, Milland, Joule, and Capa (2013) found that the negative affect associated with dissonance, which is hypothesized to be resolved via attitude change, emerges up to several minutes after the dissonance-eliciting task (in their case: an induced compliance task), and that the intensity of negative affect and subsequent attitude change were correlated.

Functional neuroimaging has been used to predict attitude change in a number of studies using the induced compliance paradigm. Attitude change is thought to occur during induced compliance when participants are unable to attribute their counter-attitudinal behaviours to a compelling external factor, such as rewards or coercion. In one such study conducted by van Veen, Krug, Schooler, and Carter (2009), participants were instructed to engage in counter-attitudinal behaviour: describing one's experience in the claustrophobic space of the MRI scanner as pleasant. Van Veen et al. showed that activation in bilateral dorsal anterior cingulate cortex and bilateral anterior insula acquired during the dissonance-arousing induced-compliance procedure predicted subsequent attitude change.

To many cognitive dissonance researchers' alarm, Chen and Resen (2010) brought attention to a potentially critical flaw with one of the most popular paradigms used to elicit attitude change. Chen and Resen were able to record behavioural measures of attitude change in a cognitive dissonance theory-consistent pattern using a free-choice-like paradigm that, while still containing the typical two rating phases, had the dissonance-inducing free-choice phase held *at the end* rather than in between the pre- and post-choice ratings phases. This finding threatened to render null years of cognitive dissonance and attitude change findings on account of a methodological oversight. Chen and Resen proposed that the discrete rating scales typically used in free-choice paradigms are not sensitive enough to accurately record participants' true attitudes, and that participants' responses in the task are simply a reflection of noise in their actually unchanging preferences. However, a subsequent experiment by Izuma et al. (2010) showed that behavioural indices of attitude change were stronger when items were put through a standard free-choice procedure with a choice condition interrupting the two ratings phases, suggesting that the presence of dissonance does indeed have a transformative effect on attitudes. Additionally, Izuma et al. found differences in neural activation during dissonance trials, compounding the evidence that the attitude change was not strictly a measurement artifact but in fact reflected real changes in underlying brain activity. Izuma et al. observed increased activity in ACC and anterior insula during dissonant trials regardless of whether the dissonance induced a positive or negative change in subsequent ratings, mirroring the results of van Veen et al., (2009) (though see Jarcho et al., 2011, which observed *reduced* activation of bilateral anterior insula during attitude change). Izuma et al. (2010) also corroborated the findings of Sharot et al. (2009) in their observation that changes in activity of the dorsal striatum, of which the caudate nucleus is a constituent, paralleled changes in stimuli rating, possibly indicating a change in hedonic value of the stimuli. Evidence that attitude change is reflected in the neural representations of preference in the ventral striatum would later be corroborated by Jarcho et al. (2011) as well.

Izuma et al. (2010) showed differential activation of bilateral DLPFC during post-choice rating trials containing cognitive dissonance-induced attitude change. The DLPFC has been linked with cognitive control and the reduction of negative affect (Botvinick, Cohen, & Carter, 2004; MacDonald, Cohen, Stenger, & Carter, 2004), particularly when resolving conflict (Mansouri, Tanaka, & Buckley, 2009). The recruitment of DLPFC may be due to the region's emotional regulatory functions, as re-evaluating one's preference for stimuli may be a means by which individuals reduce unpleasant dissonance (Berkman & Liberman, 2009). This region, specifically in the left hemisphere, has been associated with control processes involved in cognitive dissonance reduction. Harmon-Jones, Gerdjikov, and Harmon-Jones (2008) found a relative increase left-frontal cortical activity (indicated by a reduction in alpha power) during dissonance reduction in an induced-compliance paradigm, and had in an earlier study found that using feedback training to reduce relative left frontal activation decreased attitude change in the free-choice paradigm (Harmon-Jones, Fearn, Johnson, Sigelman, and Harmon-Jones, 2006). Transcranial magnetic stimulation of the posterior medial frontal cortex was also found to reduce attitude change in a modified free-choice paradigm (Izuma, Akula, Murayama, Wu, Iacoboni, & Adolphs, 2015), while transcranial direct current stimulation (tDCS) over left but not right DLPFC reduced attitude change, also in a free-choice paradigm (Mengarelli, Spoglianti, Avenanti, & di Pellegrino, 2015). Jarcho et al. (2011) noted increased activity in right but not left front cortex (particular the inferior frontal gyrus), but this was during the choice phase of a free-choice paradigm, rather than the post-choice re-rating phase. These studies point toward a rapid deployment of dissonance-reducing frontal processes as opposed to slower, reflective processes.

1.3. Conflict Monitoring and Cognitive Control

Elements from the conflict monitoring and cognitive control literature can be seen to be at work in the findings coming out of cognitive dissonance research. Cognitive control refers to the brain's capacity to adjust its cognitive settings to environmental conditions in order to perform a particular cognitive task more effectively (Botvinick, Braver, Barch, Carter, & Cohen, 2001). This ability is often divided into two separate cognitive processes. The first, conflict monitoring, is the process through which the need for additional cognitive control is established, such as through the detection of interference between different competing cognitive processes. The second process, which receives a signal from the conflict monitoring process, is the implementation of that additional cognitive control through the selection between or inhibition of one or more of the interfering processing streams. Conflict monitoring is widely thought to be a function of the dorsal ACC (Carter et al., 1998, Botvinick et al., 2004, Yeung et al., 2004) while cognitive control is implemented via the DLPFC—accordingly, fMRI studies have shown greater activity in the dACC during performance monitoring and greater activity in the DLPFC during the implementation of cognitive control (MacDonald, Cohen, Stenger, Carter, 2000; van Veen, Carter, 2001).

In terms of timing and order of activation, ACC activity thought to be reflective of performance monitoring has been verified in a number of studies to precede DLPFC "performance adjustment" activity (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). Many of these studies have made use of the high temporal resolution of event-related potentials (ERPs) to verify the order of activation of the different cognitive networks involved in conflict monitoring and cognitive control, and have proposed a number of candidate ERP components theorized to reflect these processes.

1.3.1. ERN (100ms)

The error-related negativity (ERN) is an ERP component characterized by a negative deflection that typically peaks around 100ms after a response (Yeung, Botvinick, Cohen, 2004). The ERN, detectable at fronto-central scalp sites (Gehring, Goss, Coles, Meyers, Donchin, 1993), has been source localized to the ACC (Dehaene et al., 1994; van Veen, Carter, 2002). The ERN has been interpreted to reflect “response conflict” (Carter et al., 1998), such as that which would occur during interference between a correct response and an incorrect response that is already underway (a “response reversal”), or as a result of the continued processing of the correct response after an error (Yeung, Botvinick, Cohen, 2004). The ERN has also been observed when a response reversal attempts to “correct" a correct response (Gehring et al., 1993). While many of these ERP studies have characterize the ERN as a response conflict between prepotent incorrect responses and less salient correct responses, the ERN has also been shown to indicate response conflicts to “underdetermined” responses where no response option that is more compelling than the other (Botvinick, Braver, Barch, Carter, & Cohen, 2001).

1.3.2. Conflict-N2 (200-400ms)

The Conflict-N2 (N2) is a negative peak following stimulus onset, usually peaking between 200-400ms. The N2 can be elicited during the Eriksen Flanker Task (Eriksen & Eriksen, 1974), oddball, and go–nogo tasks (Nieuwenhuis et al., 2003) and is thought to also reflect conflict monitoring (van Veen, Carter, 2002; Donker, van Boztel, 2004; Yeung, Botvinick, Cohen, 2004). As it is detectable over the same scalp regions as the ERN, the N2 has been proposed to also reflect dACC processing of a response conflict (van Veen, Carter, 2002), though whereas the ERN reflects response conflict time-locked to responses on error trials, the N2 is stimulus-locked and reflects response conflict occurring prior to responses on correct trials (Yeung, Botvinick, Cohen, 2004).

1.3.3. Conflict-N4/N450 (350-500ms)

A related component proposed to signal the processes of conflict monitoring and cognitive control has been observed in a number of studies, characterized by a negative amplitude deflection around 400ms after stimulus onset. ERP studies of the classic colour word Stroop effect found a negative deflection between 350-500ms after stimulus onset over medial dorsal scalp with neural generators sourced to the ACC (Liotti et al., 2000; Perlstein, Larson, Dotson, & Kelly, 2006; West & Alain, 1999; West, 2003). This component was thought to index the detection of conflict and the need for suppression of a prepotent response to the meaning of the word. A later study also employing the Stroop task showed a negative deflection over similar fronto-central sites around 400ms for incongruent items compared to congruent and neutral items, also source localized to the ACC (Hanslmayr et al. 2008). Other studies found negative deflections during the same time window using similar tasks, but arrived at different conclusions regarding possible neural generators. More recently, left fronto-centrally maximal negativities peaking around 400ms have been reported in response to emotional conflict raised by affective versus neutral words in emotional Stroop tasks (Deveney & Pizzagalli, 2008; Taake, Jaspers-Fayer & Liotti, 2009).

1.3.4. Conflict-SP (500-800ms)

ERP studies of the colour Stroop effect have identified a second ERP effect associated to the processing of incongruency. The Sustained Positivity (500-800ms) over predominantly left posterior scalp is more positive for Incongruent than Congruent colour words (Larson et al., 2009; Liotti et al., 2000; West, 2003; West & Alain, 1999). This effect has been suggested to reflect extra processing of the incongruent word by posterior brain areas to facilitate conflict resolution after conflict has been detected by the ACC (and reflected by the N450), suggesting that this component reflects an interaction between frontal and posterior sensory regions as part of a top-down attentional/cognitive control process (Grent-'t-Jong & Woldorff, 2007).

1.3.5. P300 (300-800ms)

Target detection in oddball tasks or tasks involving a choice between two or more stimuli typically elicit a large amplitude, broadly distributed potential with a maximum over midline centro-parietal scalp, peaking around 300ms but elapsing over several hundred milliseconds, depending on the complexity of the task. Of relevance here, P300 amplitude has been found to be enhanced by motivational salience of an event for both emotional (Hajcak et al, 2010) and rewarding stimuli (Wu & Zhou, 2009). While P300 generators are widespread within cortical structures, recent combined ERP-fMRI studies indicate that during tasks involving reward, P300 amplitude to targets is actively modulated in a striatocortical network originating in the ventral striatum (Pfabigan et al, 2014; Pogarell et a, 2011). In other words, unlike the Conflict-SP, reflecting top-down cognitive control processes, P300 may be more sensitive to 'bottom-up" influences derived from the salience/reward value of the stimulus.

1.3.6. FFT and Cognitive Control

Along with ERPs, the understanding of conflict monitoring and cognitive control has been expanded by investigations of the neural oscillations associated with these processes. A number of studies have found a decrease in posterior alpha power (8-14 Hz) following response errors (Carp and Compton, 2009; Compton et al., 2010, Mazaheri et al., 2009; van Driel, Ridderinkhof, Cohen, 2012) indicating increased cerebral activity (Compton et al., 2010) and attention (Dockree et al., 2007; Sadaghiani et al., 2010; Macdonald et al., 2011), whereas an increase of alpha power is predictive of subsequent errors in these tasks (Bengson et al., 2012). Investigations of the connection between frequency and ERPs have found that the ERN is associated with mid-line frontal theta EEG activity (Luu and Tucker, 2001; Trujillo & Aleen, 2007). Using an independent component analysis (ICA) to disassemble the ERN into its independent contributing components, it was revealed that the largest such component produced theta oscillations (Makeig et al., 2002). Transient increases in mid-line frontal theta activity has further been observed after receiving task performance feedback (Gevins et al., 1989; Luu, Tucker, & Makeig, 2004) and can anticipate error responses (Luu, Tucker, Makeig, 2004). This midline frontal theta activity has also been correlated with theta activity over left lateral frontal scalp (Gevins et al., 1989). Theta oscillations around 600ms sourced to the ACC during a Stroop task increased in step with conflict processing (Hanslmayr et al. 2008). Phase coupling between ACC and left prefrontal cortex for incongruent items in the same study provided evidence of recruitment of cognitive control processes. A later study using a flanker task also noted theta phase synchrony between media frontal cortex and left frontal cortex, suggestive of processes engaged to control response conflict (Nigbur et al., 2012).

1.4. Present Study

Although well-represented in the literature in behavioural and fMRI studies, to date there have been no ERP studies of cognitive dissonance and attitude change, nor any electrophysiological studies of the free-choice paradigm. In the absence of these, the specific time course of activity during cognitive dissonance and attitude change remains unclear. Using a task inspired by the free-choice paradigm used in behavioural and fMRI studies, the present study measured ERPs and event-related oscillations in order to explore the cognitive processes engaged during difficult, dissonance-inducing decision-making that results in subsequent attitude change.

1.4.1. Hypotheses and Predictions

A free-choice between two similarly liked (or disliked) items would likely produce an underdetermined response conflict, with no objective sense in which the response is “correct” or made in “error”. Personal preference of a specific item is highly variable and intrinsically subjective, but for each individual such choice is likely to produce cognitive conflict, not dissimilar from what typically found in the Stroop task. Therefore, two ERP components of interest for this study will be conflict negativities occurring between 200-400ms (Conflict-N2) and 350-500ms (Conflict-N4) after stimulus onset. For the free-choice phase, we predicted greater voltage negative deflections over fronto-central and lateral frontal scalp arising from the response conflict in dissonant compared to consonant trials in a 250-350ms time window. As the conflict-N4/N450 in similar studies is thought to be produced as a result of conflict monitoring and prepotent response suppression in the dACC, for the post-choice re-rating phase we anticipate more negative fronto-central activity during a 375-500ms time window for re-rating of items that appeared in free-choice phase dissonant pairs, as well as in trials that contain cognitive dissonance-reducing attitude change. We also anticipate greater negativity in left frontal scalp to coincide with execution of cognitive control in left DLPFC and engagement of emotional down-regulation of dissonance-related negative affect. We also predict a modulation of a subsequent late posterior positivity as a result of either further processing of dissonance by posterior brain areas through a “top-down” process (resulting in conflict-SP), or, alternatively, we predict modulation of a posteriorly distributed P300 as a result of a "bottom-up" influence of the rewarding value of the choice. In such case, we hypothesize such Late Positive complex to be of greater amplitude for consonant than dissonant trials.

For the JTF analysis in the post-choice re-rating phase, we predict a greater reduction of fronto-central alpha power in dissonant trials compared to consonant trials to coincide with greater cortical activity, and a greater increase in fronto-central theta power during dissonant trials compared to consonant trials and in trials containing dissonance-reducing attitude change compared to trials without dissonance-reducing attitude change (reflecting the increased load on the conflict monitoring processes), and greater theta power over the left frontal region to reflect cognitive control-engagement and emotion down-regulation.

Chapter 2. Methods

2.1. Participants

Participants were 37 undergraduate students from Simon Fraser University's psychology department (4 male; M_{age} = 19.27, SD_{age} = 1.67) who completed the study for course credit. All participants gave informed consent before participating in the two hour EEG session. The participants were self-reported to be free from neurological or psychiatric illness, developmental disorder, sleep disorder, head injury, and psychotropic prescription medication. All aspects of the study were approved by the Simon Fraser University Research Ethics Board. All participants reported being right-handed. Participants were asked an open-ended question about any dietary restrictions to which they adhered, as well as hunger levels (out of 10) before, during, and after the EEG task, as this could have consequences given the food-based stimuli used in the paradigm.

2.2. Materials

Stimuli were presented using the E-Prime presentation software (Psychological Software Tools). Stimuli consisted of 216 images of various food items. The number of items was chosen to allow for the maximum number of items to be seen by participants while still allowing the full procedure, including EEG cap setup, removal, and debriefing, to be completed within two hours. Participants were fitted with an EEG cap and led into an electrically-shielded and sound-attenuating booth in which they sat approximately 60cm in front of a computer monitor and had a keyboard placed in their lap.

2.3. Procedure

We used a free-choice paradigm modelled after Izuma et al. (2010) and which we adapted for an ERP study. The paradigm consisted of three tasks: (i) the pre-choice initial item rating, (ii) the free-choice decision task, and (iii) the post-choice re-rating (Figure 1). All three tasks were performed inside the booth while EEG was continuously recorded.

Part 1: Pre-choice initial rating. After a brief practice session, participants were shown the 216 food item images and were instructed to rate each on a scale of 1 to 10 in terms of how desirable they found each item. Items were presented sequentially and randomly. Each item was displayed on screen for three seconds regardless of when or whether the participant provided a response. A fixation cross then appeared for a random inter-stimulus interval between 500 and 1000 milliseconds.

Part 2: Free-choice decision. After participants rated the 216 items in the pre-choice rating phase, their responses were processed using an external program which arranged the items into 108 unique pair presentations. Items rated 1 or 10 were excluded from the pairings to avoid floor and ceiling effects—changes in attitude cannot be accurately measure for items where change in ratings was only possible in one direction. No item appeared in more than one pair presentation. Item pairs were presented randomly. A fixation cross was present at all times between each pair of items. *Consonant* trials consisted of disparately rated items (ie: items rated 2 and 9, 3 and 7, etc.) whereas d*issonant* trials were composed of similarly rated items (ie: items rated 4 and 4, 5 and 5, 6 and 6, etc.). In order to increase power in the *dissonant* condition, 70% of the trials were coded to be dissonant pairs, while the remaining 30% were coded to be consonant pairs. These ratios are comparable to what was used in Sharot et al. (2009), where 66% of trials were dissonant and 33% were consonant. Participants were then instructed to indicate which item in each pair they preferred by choosing either the left item (using their left index finger on the '1' key) or the right item (using their right index finger on the '2' key). Item pairs appeared on screen for three seconds regardless of when or whether a response was provided.

Part 3: Post-choice re-rating. In the final phase, the 216 items were presented individually once again, though this presentation differed from the pre-choice rating phase in that the items were now arranged into an equal number of *previously selected* and *previously rejected* blocks, depending on participants' response in the free-choice decision phase. A screen displaying the words “previously selected” or “previously rejected” preceded each block. Participants were then instructed to re-rate the items on the same 1 to 10 scale. The arrangement of items into “previous-” blocks was done to alert participants to the consistency between their preferences (liking or disliking as indicated by their ratings) and their past behaviour (selecting or rejecting in the free-choice decision phase). Attitude change was measured by subtracting the initial pre-choice rating from the subsequent post-choice re-rating. At the conclusion of the task, participants were taken out of the booth and had the EEG cap removed. Participants were then debriefed.

2.4. EEG Recording

A 64 channel Ag/AgCl BioSemi electrode cap at standard 10-20 sites FP1 FPz, FP2, AF3, AF4, AFz, AF7, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, P9, P7, P5, P3, P1, Pz, P2, P4, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, Iz (BioSemi Active Two, Amsterdam) was used to record electroencephalogram (EEG) activity. Additional external electrodes were placed at left and right mastoids, external canthi (horizontal eye movements), and below each eye (vertical eye movements). Voltages were recorded against a common mode sense (CMS) active electrode. Data were sampled at 512 Hz and filtered offline (0.01 Hz high pass, 30 Hz low pass). Data was re-referenced to average mastoids. Blink and eye movement artifacts were automatically detected and rejected using FieldTrip's Z transform method (Oostenveld, Fries, Maris & Schoffelen, 2011). Average ERPs for the two free-choice pair decision conditions (consonant / dissonant), the two post-choice re-rating conditions (consonant items / dissonant items), and the two dissonant item attitude change conditions (theory-consistent / theory-inconsistent) were time-locked to stimulus onset with epoch between -200ms and 1000ms.

2.5. Behavioural Analysis

Chi-square test were performed on the resulting distribution of post-choice re-rating phase trial types (consonant/dissonant × previously selected / previously rejected × positive attitude change / negative attitude change / no attitude change) to verify the presence of theory-consistent attitude change. Repeated measures t-tests were conducted to compare reaction times (RTs) between consonant trials, dissonant trials, and attitude change trials. A repeated measures ANOVA was performed on attitude change measures using two within factors of trial type (consonant / dissonant) and choice (selected / rejected).

2.6. ERP Analysis

Time windows and regions of interest (ROIs) for analysis were determined by the a priori predictions of regional effects and by visual inspection of grand average waveforms and their difference waves. For the free-choice decision phase, we conducted a statistical analysis using a fronto-central ROI consisting of electrodes F1, Fz, F2, FC1, FCz, and FC2 with mean amplitudes averaged over a 250-350ms time region of interest (TOI) to measure the conflict-N2. For post-choice re-ratings, our ROIs for statistical analysis were a centro-parietal ROI consisting of CP1, Cpz, Cp2, P1, Pz, and P2 during a 550-650ms TOI to assess the Conflict-SP/P300, along with the fronto-central and a left lateral anterior (AF7, F7, FT7, T7) ROI during a 375-500ms time window for the Conflict-N4. For the free-choice and post-choice phases, we looked at comparisons between consonant and dissonant items. We also looked at an additional condition in the post-choice phase where we compared “theory-consistent attitude change” and “theory-inconsistent attitude change” items. The theory-consistent attitude change (“theory”) condition consisted of dissonant items from a “previously selected” block for which we recorded an increase in rating, along with dissonant items from a “previously rejected” block for which we recorded decrease in rating. Theory-inconsistent (“anti-theory”) items displayed the reverse pattern: a decrease in rating for “previously selected” items and an increase in rating for “previously rejected” items. This is a condition which we hypothesized would isolate attitude change in the absence or failure of dissonance reduction processes. Items containing an absence of attitude change (“no change” items) were not included in this condition—not only would the discrete nature of our attitude change rating scale result in the inclusion of trials containing some physiological indices of preference change in both directions (Chen & Resen, 2010), focusing on trials containing attitudes that unambiguously shift in a direction counter to what cognitive dissonance would compel isolates a particularly strong contrast condition from theory-consistent attitude change and one which we thought would be illuminating when investigated.

2.7. JTF Analysis

Due to the complex neuroanatomical nature of cognitive dissonance and attitude change, a joint time-frequency (JTF) analysis was performed on the data in the post-choice re-rating phase, looking for in particular reduced low alpha (9-11 Hz) and high alpha (12-14) in the fronto-central and left lateral ROIs, and increased theta (4-8 Hz) during dissonant and attitude change trials in the fronto-central and left lateral ROIs at the 375-500ms TOI. The EEG epochs were re-referenced to the average of the mastoids and corrected for ocular artifacts using the Independent Component Analysis runICA algorithm implemented in the FieldTrip toolbox (Oostenveld et al., 2011). Up to three components were identified as ocular artifacts and extracted from the data. The EEG was deconvolved using a multitaper method with Hanning tapers. The entire length of the time window was used for deconvolution, with a frequency range of 2 to 70 Hz in steps of 0.5 Hz.

Chapter 3. Results

Data from nine participants was excluded from analysis because of problems with EEG collection during the post-choice re-rating phase, either from crashes or slow drift, leaving 28 participants' data for analysis.

3.1. Behavioural Results

3.1.1. Post-Choice Re-rating Trial Types

Following the post-choice re-rating of items, consonance and dissonance trials were retroactively classified into sub-categories depending on the post-choice re-rating block (previously selected or previously rejected) and attitude change direction (up, down, or no change), for a total of 12 different trial types. The results can be found in Table 1. A graphical demonstration of the change in attitudes can be found in Figure 2. Behavioural results fell within anticipated patterns of cognitive dissonance-elicited attitude change. Among consonant trials (where cognitive dissonance and attitude change should be absent), a plurality of trials fell into the combined *no change* trial types (19% and 25% respectively; 44% total). In fact, for these dissonance-free consonant items, *previously-selected up* and *previously-rejected down* trials (the two sub-categories that would be most represented according to theory in the presence of cognitive dissonance) were the two least represented trial types (N = 823, N = 897; 10% and 12% respectively). Among dissonant trials, attitude change trials in the predicted dissonance-resolving direction (*previously-selected up* and *previously-rejected down*) were the most common, making up 48% of dissonance trials (23% and 25% for previously-select up and previously-rejected down, respectively). A Chi-squared tests of independence was significant for both consonant trials, χ^2 (2, N = 1578) = 49.015, $p < 0.001$, and for dissonant trials, χ^2 (2, N = 3652) = 152.777, $p < 0.001$. See Tables 2 and 3.

3.1.2. Reaction Times

In the free-choice decision phase, RTs to consonant pairs (M = 994.12, SD = 157.49) were significantly faster than dissonant pairs (M = 1194.96, SD = 215.66; *t*(25) = 8.147, p < 0.001). See Figure 3. For post-choice re-ratings, RTs were significantly faster for re-rating of items that came from free-choice *consonant* trials (M = 1322.89, SD = 229.02) than those that came from *dissonant* trials (M = 1462.36, SD = 243.29; *t*(25) = -5.806, p < 0.001). See Figure 4. The post-choice re-rating *dissonant* trials were sub-divided into a*ttitude-change present* (previously-selected up combined with previously-rejected down) and *attitude-change absent* (previously selected no change combined with previously rejected no change) trials. Though reaction times in a*ttitude-change present* trials (M = 1440.07, SD = 252.35) were slower than those in *attitude-change absent* trials (M = 1408.33, SD = 220.31), they were not significantly so, *t*(25) = 1.488, p = 0.149ns. A third condition of *attitude-change theory-inconsistent* trials (previously-selected down combined with previous-rejected up) that included trials containing attitude change in the *opposite* direction anticipated by cognitive dissonance theory was also included in the RT analysis. This theory-inconsistent condition was thought to be potentially illuminating because it would isolate the processes behind attitude change but in the absence of dissonance reduction processes (or attitude change *despite* dissonance reduction). These theory-inconsistent trials were significantly slower (M = 1484.66, SD = 242.99) than both attitude-change present trials (*t*(25) = 2.588, p = 0.016) and attitude-change absent trials (*t*(25) = 3.457, p = 0.002). See Figure 5.

3.1.3. Attitude Change

For post-choice dissonant trials, attitude change was more negative for previously rejected items (M = -0.30, SD = 0.13) than for previously selected items (M = 0.02, SD = 0.13). For consonant trials, previously selected items were much more negative (M = -0.52, SD = 0.14) than for previously rejected items (M = 0.19, SD = 0.1). See Figure 6. Repeated measures ANOVA revealed no significant main effects in attitude change between consonant trials and dissonant trials (*F*(1, 27) = 0.037, p = 0.849), or between previously selected items or previously rejected items (*F*(1, 27) = 2.579, p = 0.12). However, there was a significant interaction of trial type (consonant /

dissonant) by previous choice (rejected / selected), $F(1, 27) = 26.879$, $p < 0.001$. Paired t-tests between dissonant selected and dissonant rejected revealed a significant difference, $t(27) = 3.961$, $p < 0.001$.

3.2. ERP Results

Repeated measures t-tests were performed on fronto-central, centro-parietal, and left lateral frontal ROIs at their corresponding TOIs. Alpha was set to 0.05.

3.2.1. Free-Choice Decision (Consonant vs Dissonant). Conflict-N2

In the free-choice decision phase, scalp potentials for dissonant choice trials (M = -9.6547, SD = 5.3538) were significantly more negative than for consonant choice trials (M = -8.2258, SD = 4.8388) over the fronto-central ROI between 250-350ms, $t(27) = 3.0535$, $p = 0.005$. See Figure 7.

3.2.2. Post-Choice Re-rating (Consonant items vs Dissonant items). Conflict-SP/P300

Re-rating of items from consonant trials (M = 8.7785, SD = 7.4741) produced significantly more positive voltage scalp potentials over the centro-parietal ROI than items from dissonant trials (M = 7.1707, SD = 5.5940) during the 550-650ms time window, $t(28) = 2.9626$, $p = 0.0062$. See Figure 8.

3.2.3. Post-Choice Dissonant Attitude Change. Conflict-N4

Within the post-choice dissonant items, those trials that resulted in attitude change in the cognitive dissonant theory-inconsistent direction had significantly more negative voltage amplitudes over the left lateral frontal ROI (M = -6.572, SD = 6.2122) compared to attitude change in the theory-consistent direction (M = -4.334, SD = 7.1907) in the 375-500ms time window ($t(28) = -2.7969$, $p = 0.0092$). See Figures 9 and 10. As we hypothesized that scalp amplitudes on left lateral frontal ROI scalp corresponded to emotional down-regulation and attitude change, we compared the relationship between the amplitudes and behaviour attitude change measures. We found a positive correlation between the left lateral frontal ROI and theory-consistent attitude change in trials containing dissonant items ($r(28) = -.643$, $p < 0.001$) but not for consonant items ($r(28) = -0.181$, $p = 0.356$ns), with scalp potentials growing more negative as the magnitude of dissonance-elicited attitude change increased. See Figures 11 and 12.

3.3. JTF Results

3.3.1. Post-Choice Re-rating (Consonant items vs Dissonant items)

Paired-samples t-tests were performed for fronto-central and left lateral frontal ROIs in the theta, low alpha and high alpha frequencies during the 375-500ms TOI. Alpha was set to 0.05.

There was a significant difference in high alpha power between conditions over fronto-central scalp at the 375-500ms time window ($M_{consonant} = -2.42$, $SD_{consonant} = 4.58$; $M_{dissonant} = -3.17$, $SD_{dissonant} = 3.93$; $t(30) = 2.473$, $p = 0.019$). See Figure 13. At the left lateral ROI, there was a greater reduction in high alpha power relative to baseline for dissonant items ($M_{dissonant} = -2.23$, $SD_{dissonant} = 5.89$) than for consonant items ($M_{consonant} = -1.51$, $SD_{consonant} = 5.32$) between 375-500ms ($t(30) = 2.692$, $p = 0.012$). See Figure 14. All other comparisons were non-significant.

3.3.2. Post-Choice Dissonant Attitude Change (Theory vs Anti-Theory)

Paired samples t-tests were performed for fronto-central and left lateral frontal ROIs in the theta, low alpha and high alpha frequencies during the 375-500ms TOI. Alpha was set to 0.05.

There was a significant difference in theta power between conditions over fronto-central scalp at 375-500ms ($M_{theory} = -0.04$, $SD_{theory} = 0.94$; $M_{anti\text{-}theory} = -0.82$, $SD_{anti\text{-}theory} = 1.66$; $t(30) = 3.66$, $p < 0.001$). There was also a significant difference in low alpha power over fronto-central scalp between 375-500ms ($M_{theory} = -3.47$, $SD_{theory} =$

4.13; $M_{anti\text{-}theory} = -4.81$, $SD_{anti\text{-}theory} = 6.08$; $t(30) = 2.277$, $p = 0.03$). See Figure 15. All other comparisons were non-significant.

Chapter 4. Discussion

4.1. Behavioural Effects

The breakdown of the post-choice trial types indicates that cognitive dissonance-elicited attitude changed occurred in participants as intended. Although we found a significant interaction of attitude change trial type (consonant / dissonant) and previous choice (selected / rejected), only for dissonant items do we see attitude change occurring in the theory-anticipated direction; consonant items showed not only an inverse change in attitudes (rejected items went up and selected items went down), the amount of attitude change was also greater than for dissonant items. It is possible that consonant items, having disparate very low or very high ratings (as opposed to the more mid-range neutral dissonant items) may have been more “unstable” and therefore been more susceptible to a regression toward the mean effect, similar to the one proposed by Chen and Resen (2010) and observed by Izuma et al. (2010). In the presence of dissonance-reduction processes that compels attitude change in a theory-consistent direction, there may have also been a greater “inertia” to overcome for items that participants had strongly committed to either liking or disliking (over-represented in consonant trials) compared to re-evaluating items participants had given more neutral ratings (which are over-represented in dissonant trials). Indeed, Izuma et al. found similar behavioural attitude change to ours, with items from “hard” decisions (analogous to the present study's “dissonant” items) meeting cognitive dissonance theory-informed expectations, while “easy” decision items (analogous to the present study's “consonant” items) showed attitude change in the exact reverse direction to the typical theory-informed prediction. The behaviour results of Izuma et al, and also Jarcho et al. (2011) mirror ours in another way: very little attitude change occurred in the positive direction, with most re-evaluations resulting in a more negative difference score on average. Both the present study and Izuma et al. (2010) used food images as stimuli, so it is possible that participants experience some kind of food fatigue or habituation (though participants for the present study indicated that their hunger levels increased on average[2] during the course of the experiment, it could be that they became fatigued with the *particular* images shown).

Reaction times for post-choice re-rating trials further supported the presence of cognitive dissonance. The fastest trials during the post-choice phase were those for consonant items where no cognitive dissonance was expected to be present, whereas the slowest trials were those containing attitude change in a theory-inconsistent direction. Violations of the impetus to rate rejected items lower and selected items higher seemed to incur a cognitive cost on participants' reaction times to stimuli.

4.2. ERP Effects

In the free-choice decision phase, we found a significant difference in consonant and dissonant trial ERP voltages at the fronto-central ROI during the Conflict-N2 time window. The more negative voltage over fronto-central scalp during dissonant trials likely reflects ACC conflict monitoring responding to the difference in difficulty between easy, disparate consonant choices and hard, similar dissonant choices. The free-choice decision phase did not reveal any significant differences at the centro-parietal ROI at our specified TOI corresponding to the Conflict-SP/P300. While the differences over the centro-parietal ROI were not significant during the free-choice phase, they were during the subsequent post-choice re-rating phase. This positive component was greater in voltage for trials containing consonant items compared to those containing dissonant items. The timing and scalp distribution of this late positive potential is reminiscent of the P300, a component found modulated by reward value likely through cortical projections from ventral striatum (Pfabigan et al., 2014), possibly as hedonic representations of the stimuli are adjusted. The directionality of change discounts an interpretation in terms of Conflict-SP, for which the dissonant trials were predicted to have more positive voltage than consonant trials. These findings suggest that reward signal changes in the striatum may occur (at least more reliably) during the post-choice re-rating phase rather than the

2 $M_{time1} = 3.82$, $SD_{time1} = 2.68$; $M_{time2} = 5.41$, $SD_{time2} = 2.60$; $t(32) = 5.504$, $p < 0.001$

free-choice decision phase, which concurs with the findings of Sharot et al. (2009) and Jarcho et al. (2011), both of whom identified the striatum as having a role in cognitive dissonance reduction. Alternatively, striatal activity may reflect the rewarding nature of dissonance reduction or, as suggested in Jarcho et al., centro-paretial activity during the attitude change (post-choice) phase could be attributed to self-reflection and self-reference, which may result from participants imagining how much they would enjoy the item as means to determine what rating the items should receive. Alternatively, this effect could simply be a reflection of the relative rarity of consonant items in the post-choice phase, or greater confidence in participants' re-evaluation of disparately-rated items that were untouched by the dissonance choice task.

A left frontal Conflict-N4 effect was observed, with more negative voltage in theory-inconsistent attitude change trials compared to theory-consistent attitude change trials. Voltages changes in left lateral frontal scalp were associated directly with magnitude of attitude change, as we found amplitudes over this region correlated very strongly with behavioural attitude change measures, supporting our hypothesis regarding this region. Izuma et al. (2015) and Mengarelli et al. (2015) found that disruption or interference with the normal activity of cortex beneath this left lateral frontal region of the scalp inhibited attitude change. Harmon-Jones, et al. (2008) suggested this region is likely involved in dissonance reduction processes. Jarcho et al. (2011) later found that right rather than left frontal cortex was associated with attitude change but our data does not corroborate this finding, though it should be noted that Jarcho et al. analyzed activity during the free-choice decision phase rather than the post-choice re-rating phase as was the case in the present study. Regardless, Jarcho et al. suggested that prefrontal activity likely accompanied a reduction of activity in insula, given that the prefrontal cortex down-regulates distress. The strong association between this region and attitude change measures provides additional evidence against the "deviation toward the mean" hypothesis that attempted to explain away attitude change produced by cognitive dissonance (Chen and Resen, 2010). That this lateral region is active before the centro-parietal region further lends credence to the "down-regulation" interpretation: frontal cortex responds to negative affect first, and then consolidates changes to the hedonic representations of the stimuli in the striatum in response. Our findings also support the view that cognitive dissonance-elicit attitude change occurs rapidly, within the first 1000ms, without the need of extensive conscious reflection or rationalization.

4.3. JTF Effects

While the finding of greater (high) alpha power over fronto-central and left lateral scalp for consonant trials compared to dissonant trials in the post-choice phase (and greater theta power for theory-consistent compared to theory-inconsistent attitude change trials) was consistent with our predictions, counter to predictions we found a smaller reduction of (low) alpha power for theory-consistent attitude change trials compared to theory-inconsistent attitude change trials over fronto-central electrode sites. These results seem to indicate greater cortical activity during conflict monitoring when attitudes change in the *opposite* direction from what cognitive dissonance would encourage, as if these changes occur despite negative emotional affect. Harmon-Jones et al. (2008) interpreted greater left frontal cortical activity (reflect by a decrease in alpha power) during dissonance reduction to be indicative of commitment to action (in this case, dissonance reduction behaviours) via approach motivation processes. This finding would be consistent with our behavioural observation that theory-inconsistent attitude change trials recorded longer reaction times compared to theory-consistent attitude change trials. If indeed these results indicate a defiance of the impulse to make a dissonance-reducing preference shift, overcoming the dissonance-reduction response appears to follow a period of more intense response conflict where the impulse to reduce dissonance interferes maximally with an eventual dissonance-*enhancing* response. The question remains though of what would be participants' motivation to resist the dissonance reduction impulse. It could be possible that this response is performed outside of awareness, similar to how the ERN can be detected even when participants are unaware of having made an error (Nieuwenhuis et al., 2001), and that some other concern, motivation, commitment, or strategy takes precedence over the subconscious need for dissonance reduction.

Despite our compelling ERP findings suggesting engagement of cognitive control and down regulation processes, we failed to find any differences in alpha or theta power for left frontal electrode sites between theory-consistent and theory-inconsistent attitude change conditions. That we detected differences in alpha power in the fronto-central electrode sites suggests the possibility that there was increased activity in frequencies that we did not investigate, such as those in the gamma band.

4.4. Limitations and Future Directions

The most notable limitation of the current study was that we did not track the changes in scalp amplitudes for each of the 216 items between pre-choice and post-choice phases. Had we done so we could have performed a direct comparison between the difference in amplitudes between the pre- and post-choice phases and the centro-parietal ROI thought to reflect striatal activity. With such a comparison in hand, we would have had an electrophysiological counterpart to the BOLD analyses performed in Izuma et al. (2010) and Sharot et al. (2009) which compared striatal activations in pre- and post-choice rating phases. In these studies, a strong correlation between striatal activity and subsequent attitude change was found.

There are a few avenues worth exploring for future iterations of this study, or for investigations of the neurophysiology of cognitive dissonance and attitude change in general. First, it might be worth observing if there are any differences that result from providing participants with some indication of their prior ratings of items that reappear in the post-choice re-rating phase. In the present study, participants only received information regarding whether or not a specific item had been previously selected or rejected during the earlier free-choice decision phase. The rationale for not including a reminder of the participant's previous rating was that cognitive dissonance is thought to be subconscious process that would alter participants' subjective value of the items without explicit attention or intention. Including a reminder of participants' prior ratings would lighten the burden of memory (if indeed participants were actively attempting to remember their previous ratings rather than simply responding in accordance to a genuine “revised” hedonic evaluation of the items), but this could also have the effect of measuring a different flavour of attitude change, one that is a result of conscious reflection rather than unconscious reflex, with possible behavioural and electrophysiological consequences.

Three final suggestions are that 1) for future studies, it would be useful to change the stimuli from food to items from a different category, both to eliminate the possibility of the “hunger” confound and to test the generalizability of the findings. 2) To include fewer “neutrally” rated items for dissonance trials (such as those rated a “5” in the pre-choice phase). Choice between two neutrally-rated items no doubt produces a response conflict, but it is unlikely to enhance dissonance. A choice between more polarized liked or disliked items would produce a more unambiguously “dissonant” conflict. And 3), in light of the finding of significantly reduced alpha power without an accompanying increase in theta power, it would be prudent to investigate the nature of any gamma oscillations over frontal scalp in the post-choice phase.

Jarcho et al. (2011), citing an observation by Brehm (1956) that only a fraction (27-59%) of the population demonstrates cognitive dissonance-related attitude change. Bein only interested in this phenomenon, Jarcho at al. excluded 40% of their participants from their analysis because those participants did not demonstrate measurable attitude change. Our pool of participants fared slightly better, with only 23% failing to demonstrate attitude change in our dissonant conditions. Nevertheless, our analysis included data from all participants, including the non-attitude changers.

Our study represents the first ERP investigation of cognitive dissonance and attitude change, and the first electrophysiological study of the free-choice paradigm. Our findings generally align with those observed in behavioural and neuroimaging studies over the last several decades, and we have further contributed to the evidence showing that cognitive dissonance can occur rapidly within seconds and is not restricted to being a process of slow, deliberate, more conscious self-reflection.

Figures

Figure 1 Free-Choice Paradigm

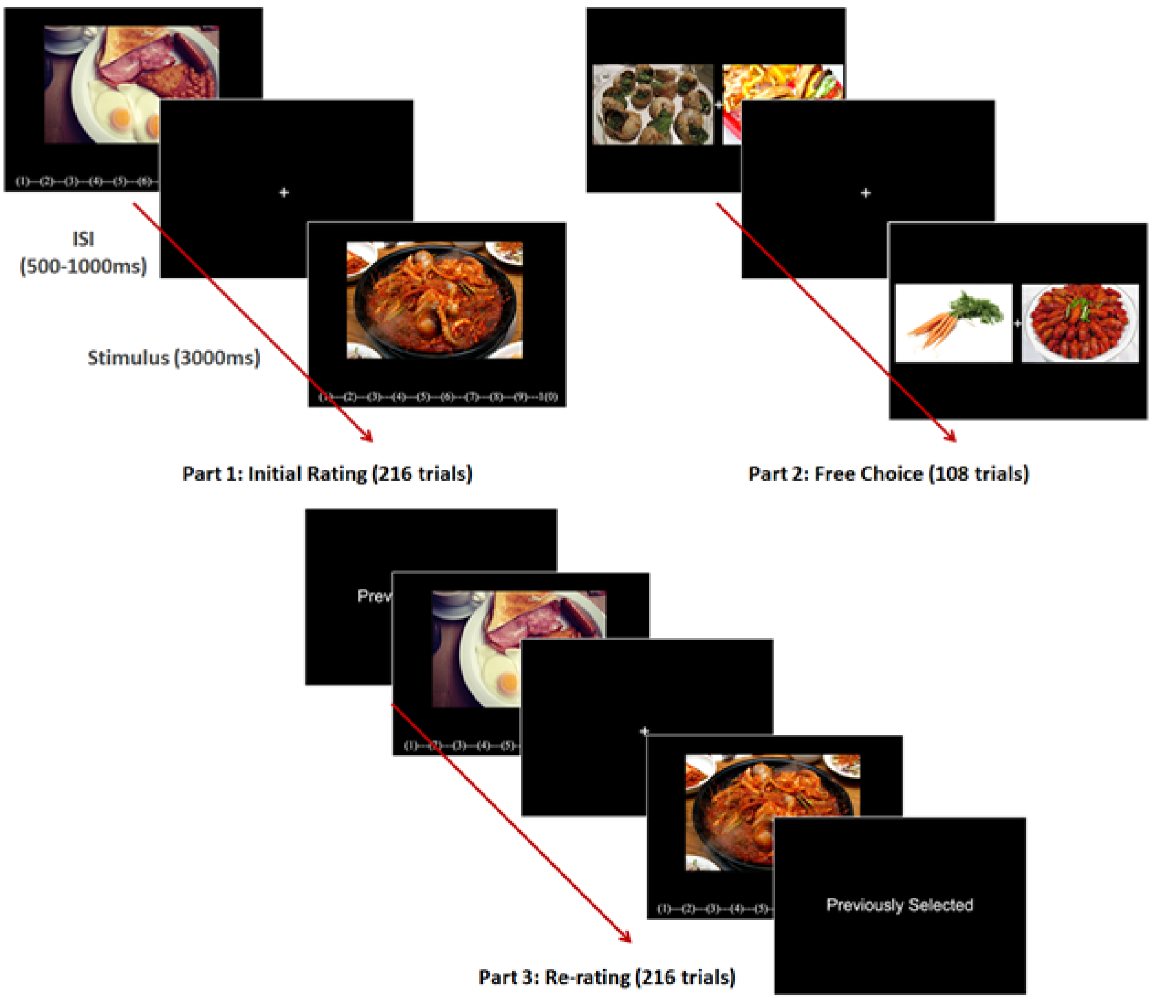

Figure 1 Part 1 (Pre-choice), Part 2 (Free-choice), Part 3 (Post-choice)

Figure 2 Trials Types

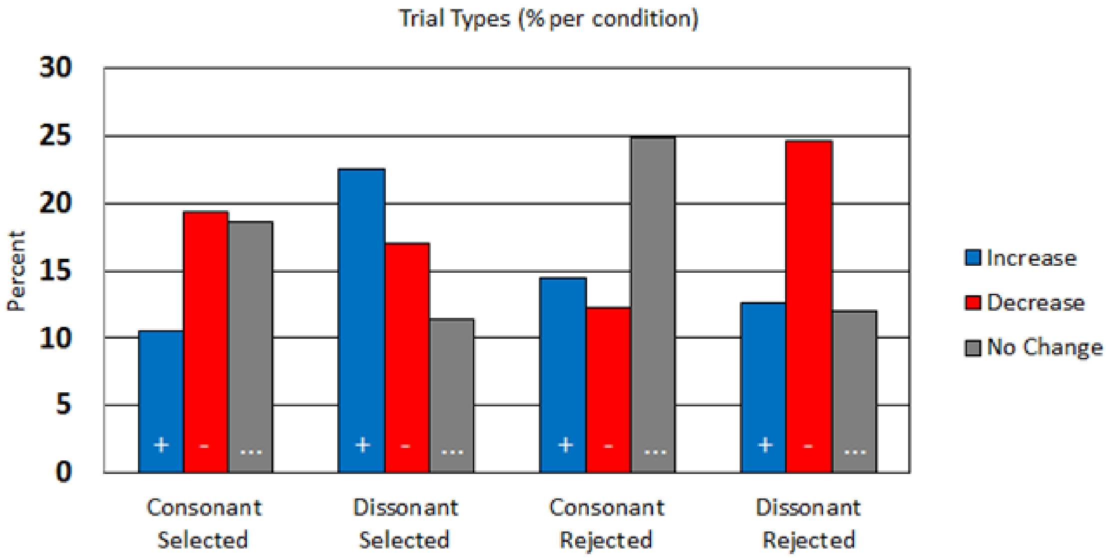

Figure 2 Change in rating (post-choice – pre-choice): “+” = increase in rating; “-” = decrease in rating; “...” = no change

Figure 3 Free-Choice Reaction Times

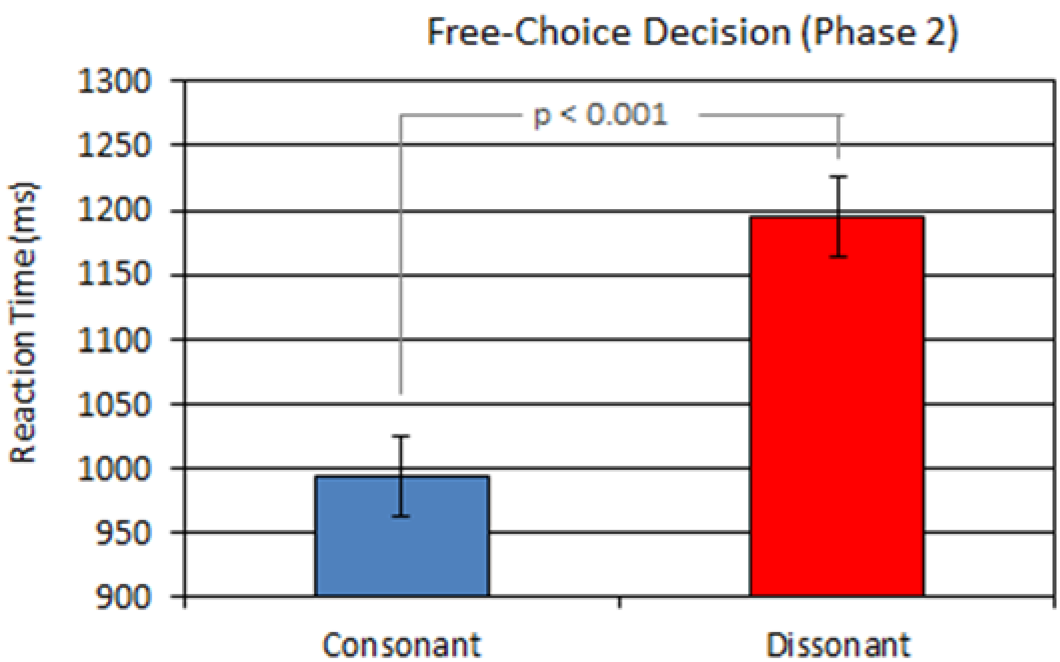

Figure 4 **Post-Choice Reaction Times**

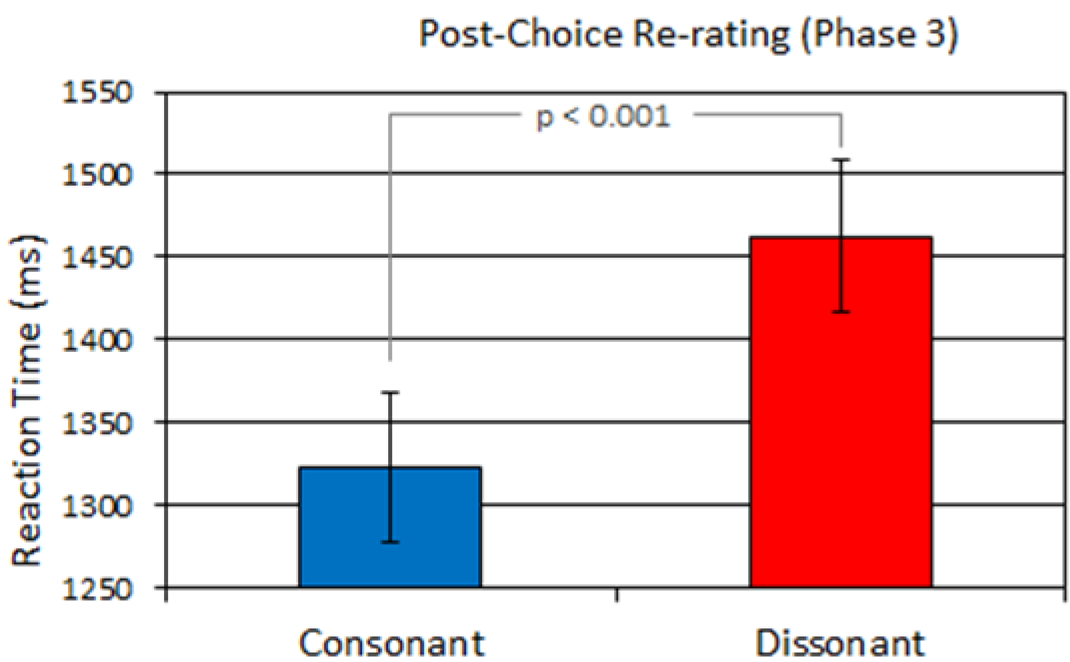

Figure 5 Post-Choice Reaction Times (Dissonant Attitude Change)

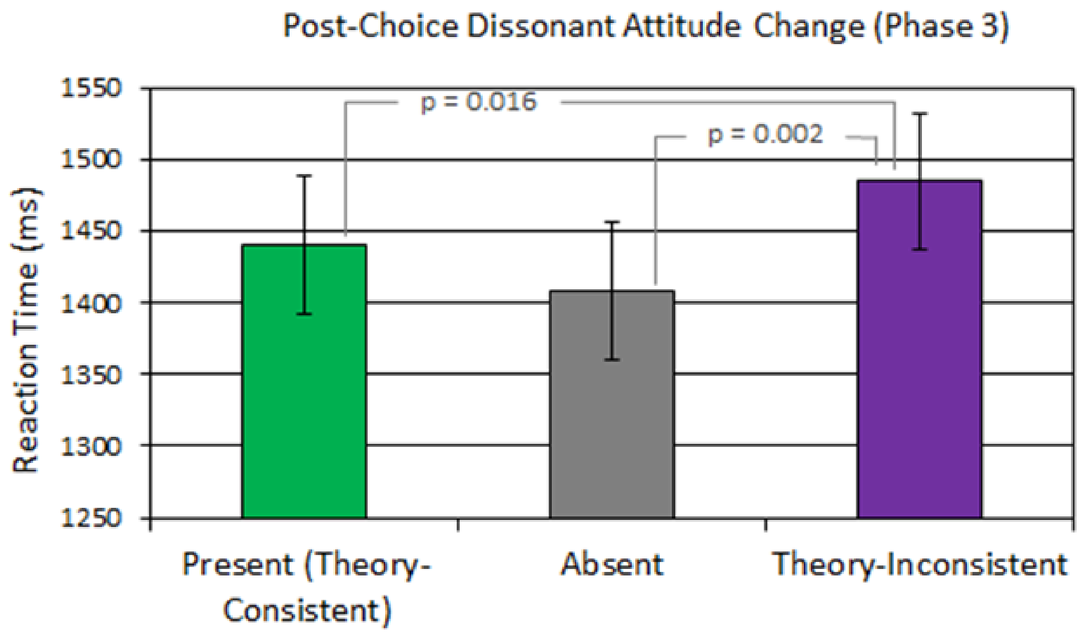

Figure 5 Present: previously-selected up trials + previously-rejected down trials; Absent: previously selected no change trials + previously rejected no change trials; Theory-inconsistent: previously-selected down trials + previous-rejected up trials

Figure 6 Behavioural Attitude Change

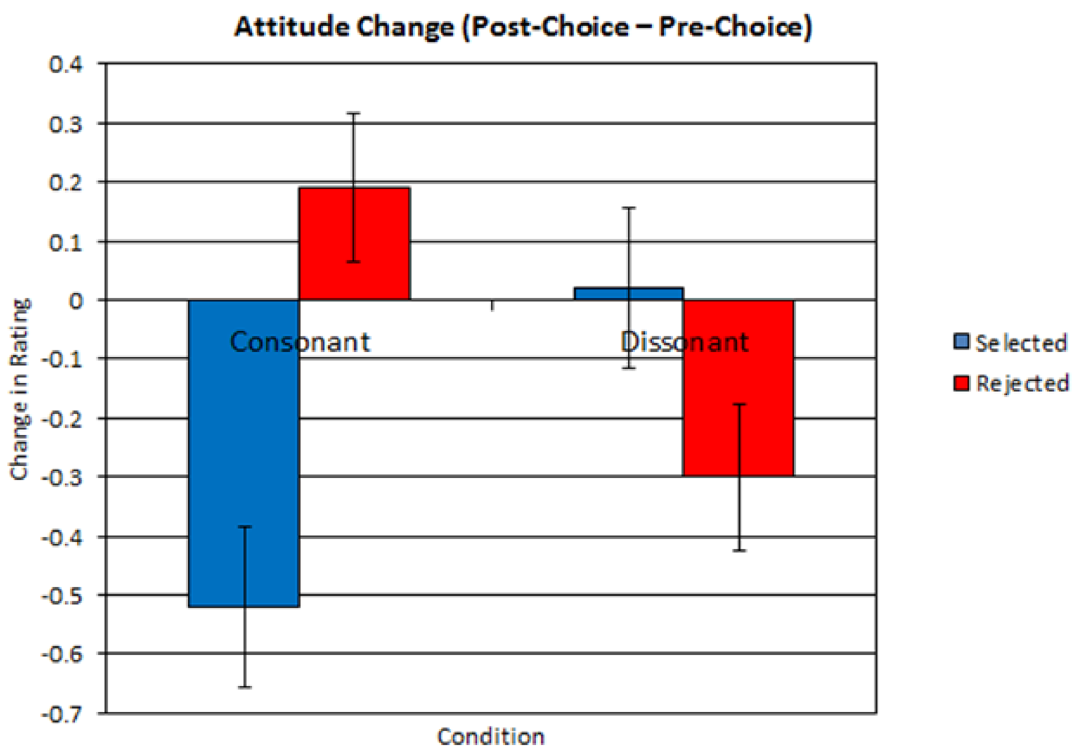

Figure 7 Free-Choice ERP

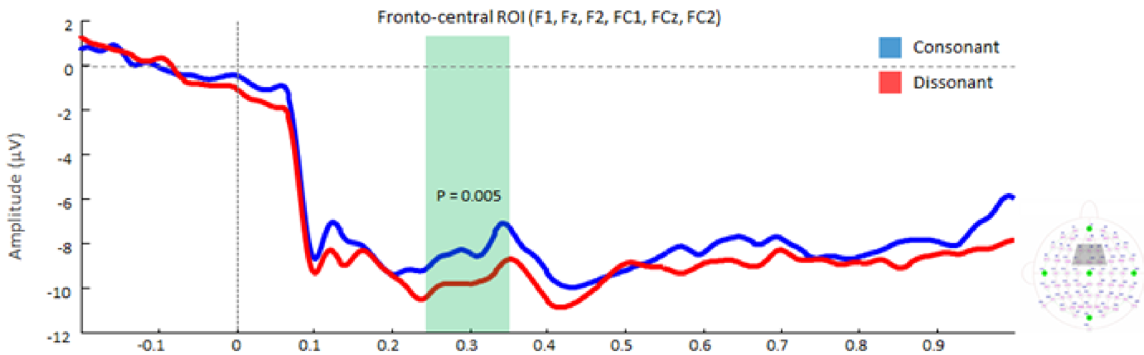

Figure 8 Post-Choice ERP (Centro-Parietal)

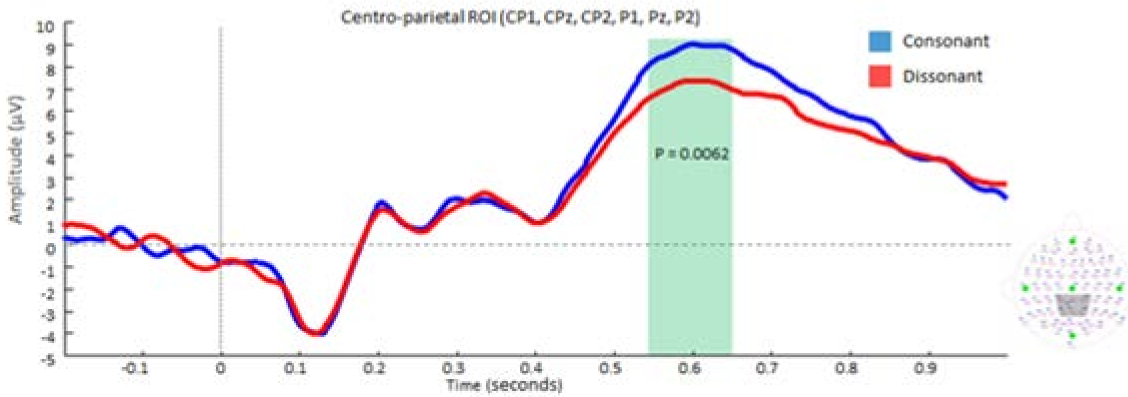

Figure 9 Post-Choice ERP (Left-Lateral Frontal)

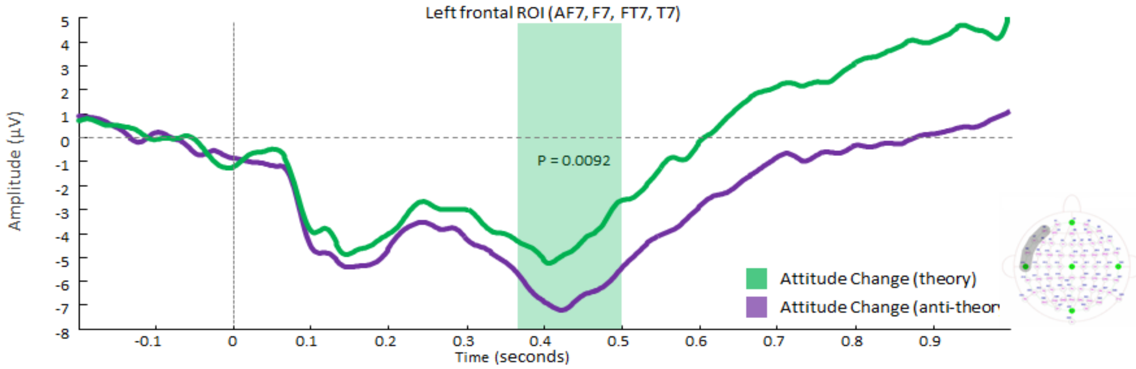

Figure 10 Post-Choice Theory vs. Anti-Theory ERP

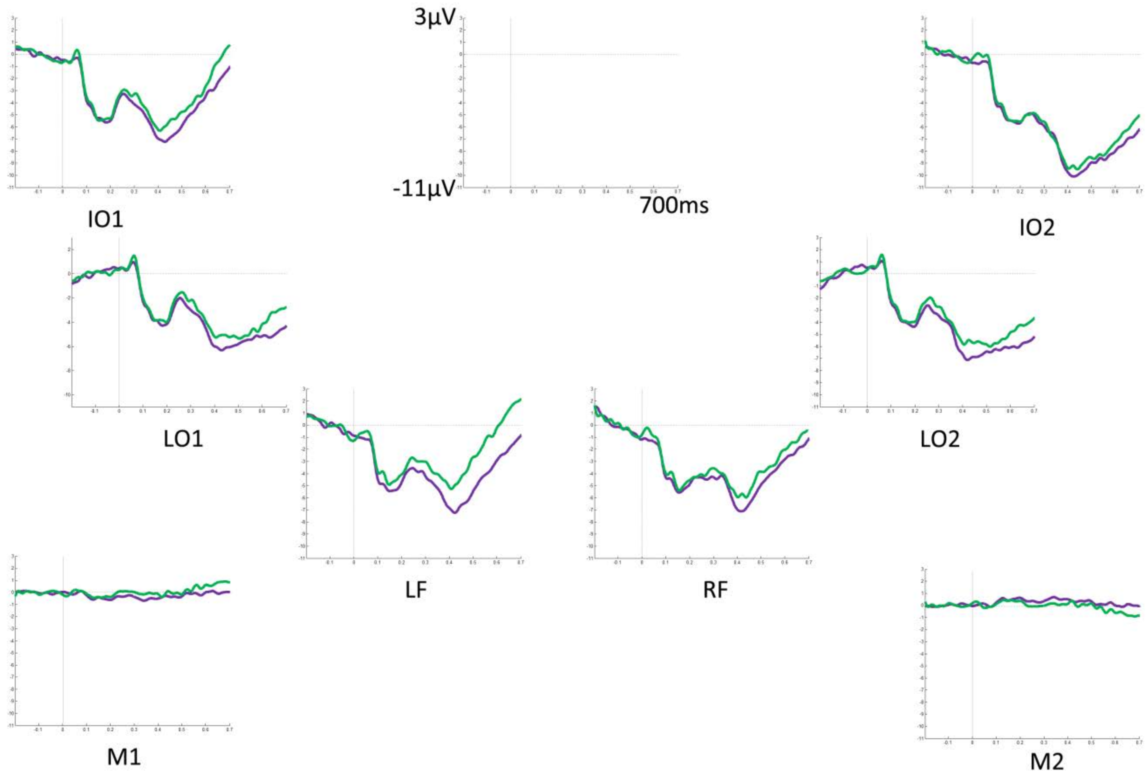

Figure 10 ERPs for post-choice theory-consistent (green) and theory-inconsistent (purple) attitude change. Epoch shown is from -200ms to 700ms. M1/M2 show the ERPs at left and right mastoids; LO1/LO2 show the lateral orbital electrodes; IO1/IO2 show the infraorbital electrodes. LF shows the ERP for the left-lateral frontal ROI; RF shows the ERP for the corresponding right-lateral frontal electrodes.

Figure 11 Post-Choice Dissonant Correlation

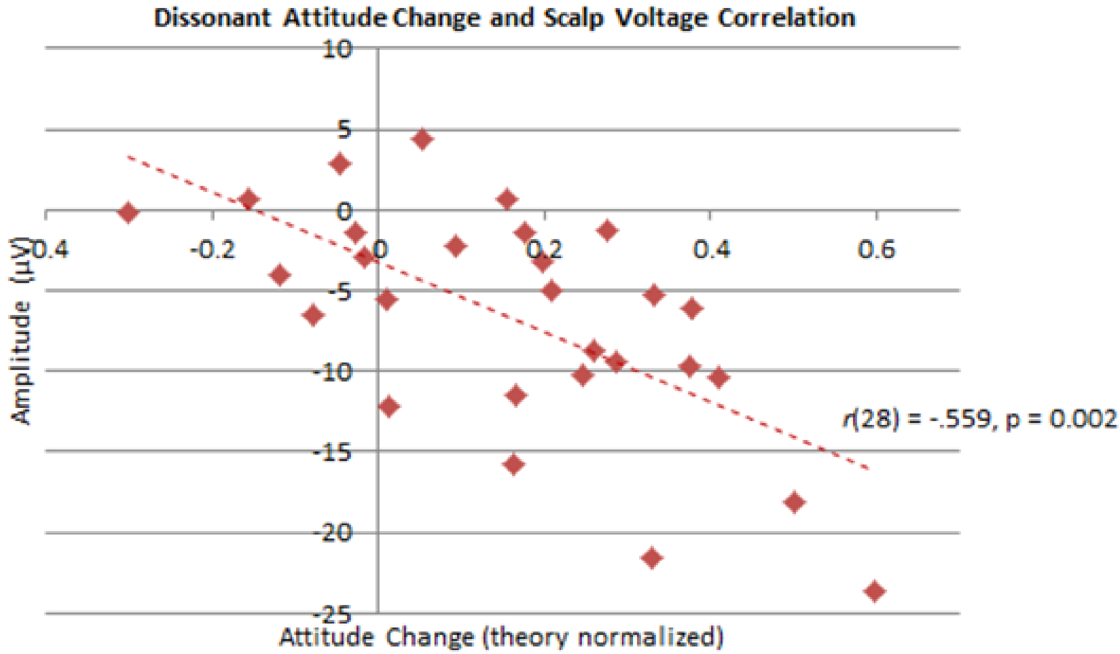

Figure 11 Correlation between change in ratings (post-choice – pre-choice) and scalp potential in dissonant items

Figure 12 Post-Choice Consonant Correlation

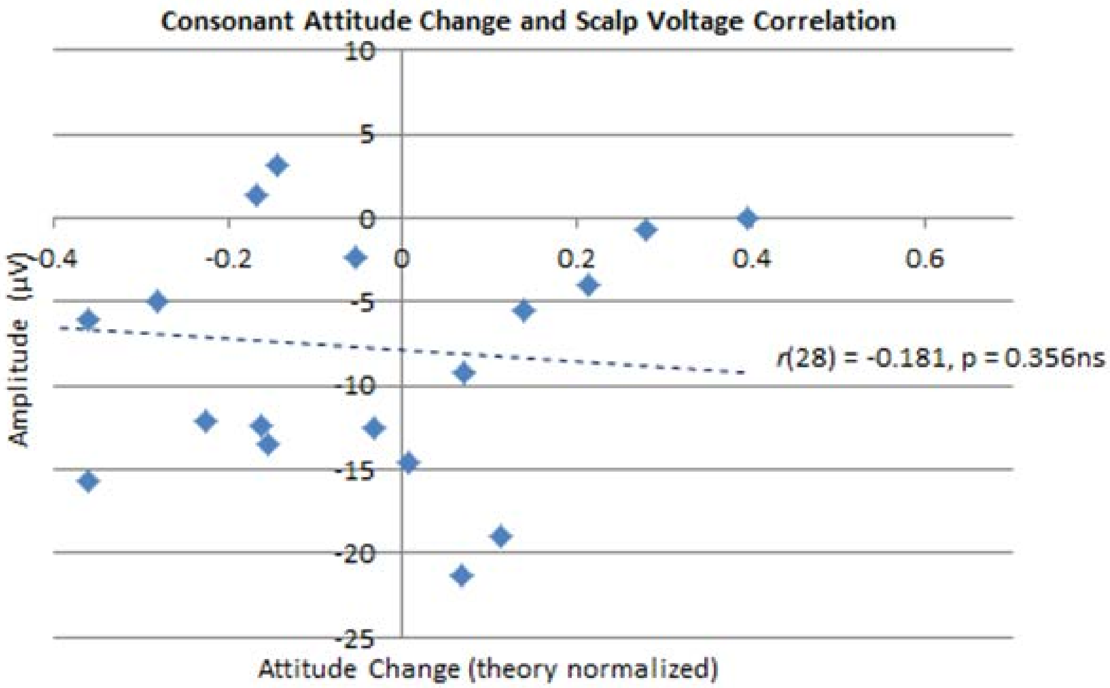

Figure 12 Correlation between change in ratings (post-choice – pre-choice) and scalp potential in consonant items

Figure 13 JTF Post-Choice Dissonant vs. Consonant (Fronto-Central)

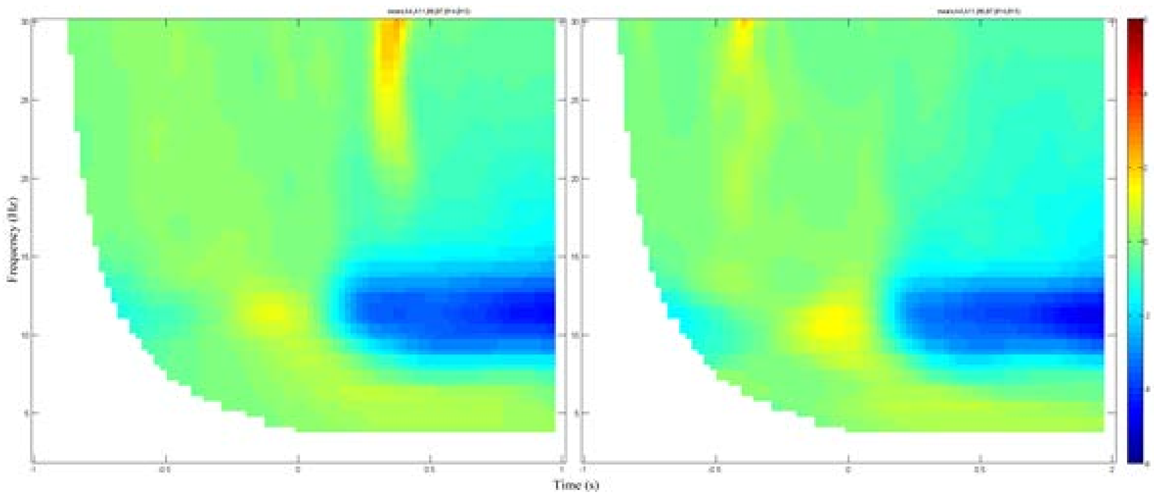

Figure 13 JTF decomposition for dissonant (left) and consonant (right) items over fronto-central ROI. Epoch shown is -1000ms to 1000ms. Y axis is frequency (1 to 30 Hz). Colour-bar indicates change in power relative to baseline.

Figure 14 JTF Post-Choice Dissonant vs. Consonant (Left-Lateral Frontal)

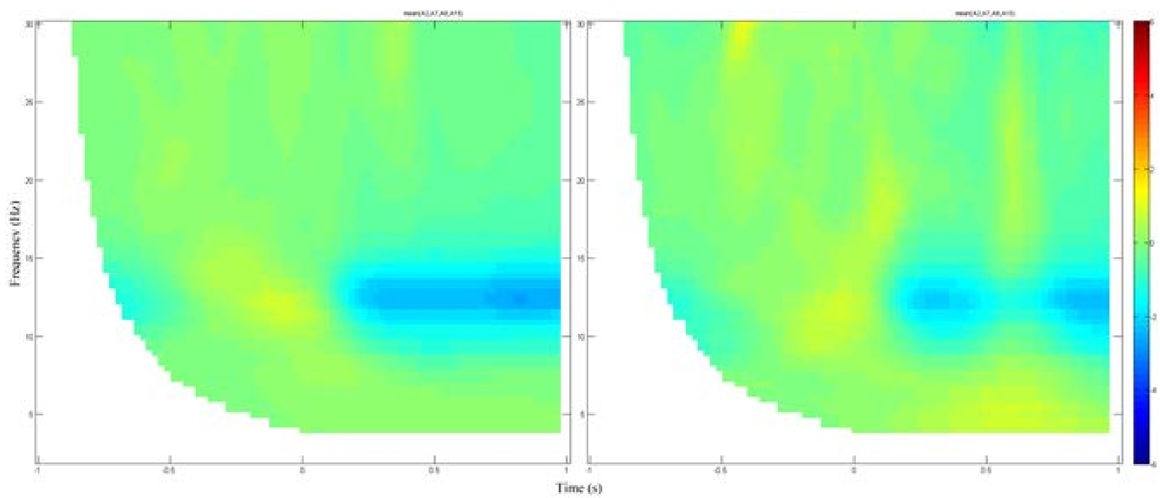

Figure 14 JTF decomposition for dissonant (left) and consonant (right) items over left-lateral frontal ROI. Epoch shown is -1000ms to 1000ms. Y axis is frequency (1 to 30 Hz). Colour-bar indicates change in power relative to baseline.

Figure 15 JTF Post-Choice Theory vs. Anti-Theory (Fronto-Central)

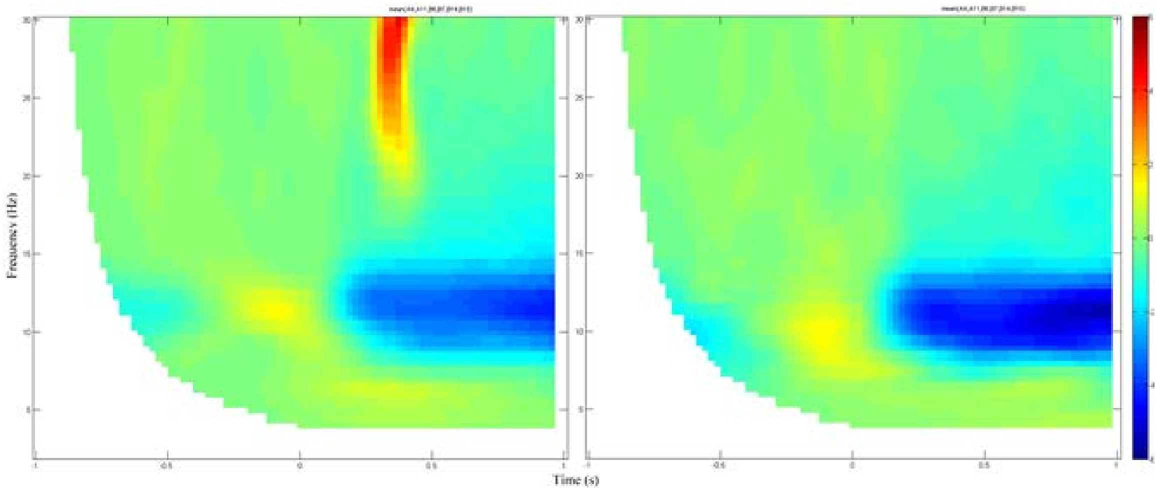

Figure 15 JTF decomposition for theory-consistent attitude change (left) and theory-inconsistent (right) over fronto-central ROI. Epoch shown is -1000ms to 1000ms. Y axis is frequency (1 to 30 Hz). Colour-bar indicates change in power relative to baseline.

Tables

Table 1 Trial Types

Condition	Choice	Rating Change			
		Up	Down	No change	Total
Consonant	Selected	166 (10.5%)	306 (19.4%)	*293 (18.6%)*	765 (48.2%)
	Rejected	228 (14.4%)	192 (12.2%)	*393 (24.9%)*	813 (51.5%)
	Total	394 (25%)	498 (31.6%)	686 (43%)	1578 (100%)
Dissonant	Selected	*823 (22.5%)*	620 (17%)	415 (11.4%)	1858 (51%)
	Rejected	460 (12.6%)	*897 (24.6%)*	437 (12%)	1794 (49%)
	Total	1283 (35%)	1517 (42%)	852 (23%)	3652 (100%)

Table 2 Trial Types Chi-Square Results (Consonant)

PrevChoice * RatingChange Crosstabulation

			RatingChange			Total
			Up	Down	No Change	
PrevChoice	Previously Selected	Count	166	306	293	765
		Expected Count	191.0	241.4	332.6	765.0
	Previously Rejected	Count	228	192	393	813
		Expected Count	203.0	256.6	353.4	813.0
Total		Count	394	498	686	1578
		Expected Count	394.0	498.0	686.0	1578.0

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	49.015[a]	2	.000
Likelihood Ratio	49.295	2	.000
Linear-by-Linear Association	.827	1	.363
N of Valid Cases	1578		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 191.01.

Table 3 Trial Types Chi-Square Results (Dissonant)

PrevChoice * RatingChange Crosstabulation

			RatingChange			Total
			Up	Down	No Change	
PrevChoice	Previously Selected	Count	823	620	415	1858
		Expected Count	652.7	771.8	433.5	1858.0
	Previously Rejected	Count	460	897	437	1794
		Expected Count	630.3	745.2	418.5	1794.0
Total		Count	1283	1517	852	3652
		Expected Count	1283.0	1517.0	852.0	3652.0

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	152.777[a]	2	.000
Likelihood Ratio	154.431	2	.000
Linear-by-Linear Association	68.360	1	.000
N of Valid Cases	3652		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 418.53.

References

Amodio, D. M., Harmon-Jones, E., Devine, P. G., Curtin, J. J., Hartley, S., & Covert, A. (2004). Neural signals for the detection of unintentional race bias. *Psychological Science, 15,* 88–93.

Bengson, J. J., Mangun, G. R., & Mazaheri, A. (2012). The neural markers of an imminent failure of response inhibition. *Neuroimage, 59*(2), 1534-1539.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences, 8*(12), 539-546.

Brehm, J. W. (1956). Post-decision changes in the desirability of choice alternatives. *Journal of Abnormal Social Psychology, 52*, 384 –389.

Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science, 280*(5364), 747-749.

Carter, C. & van Veen, V. (2007). Anterior cingulate cortex and conflict detection: An update of theory and data. *Cognitive, Affective, & Behavioral Neuroscience, 7*(4), 367-379.

Chen, M. K. & Risen, J. L. (2010). How choice affects and reflects preferences: Revisiting the free-choice paradigm. *Journal of Personality and Social Psychology, 99*, 573–594.

Compton, R. J., Arnstein, D., Freedman, G., Dainer-Best, J. and Liss, A. (2011), Cognitive control in the intertrial interval: Evidence from EEG alpha power. *Psychophysiology*, 48: 583–590. doi:10.1111/j.1469-8986.2010.01124.x

Delgado, M. R. (2007). Reward-related responses in the human striatum. *Annals of the New York Academy of Sciences,1104*, 70–88.

de Vries, J., Byrne, M., & Kehoe, E. (2015). Cognitive dissonance induction in everyday life: An fMRI study. *Social Neuroscience, 10*(3), 268-281.

Dehaene, S., Posner, M. I., & Tucker, D. M. (1994). Localization of a neural system for error detection and compensation. Psychological *Science, 5*(5), 303-305.

Delgado, M.R., Locke, H.M., Stenger, V.A. & Fiez, J.A. (2003). Dorsal striatum responses to reward and punishment: effects of valence and magnitude manipulations. *Cognitive, Affective, & Behavioral Neuroscience, 3*, 27–38.

Deveney, C. M., and Pizzagalli, D. A. (2008), The cognitive consequences of emotion regulation: An ERP investigation. *Psychophysiology*, 45: 435–444. doi:10.1111/j.1469-8986.2007.00641.x

Egan, L. C., Santos, L. R., Bloom, P. (2007). The origins of cognitive dissonance: evidence from children and monkeys. *Psychological Science, 18*, 978 –983.

Festinger, L., Henry, W., Riecken, S. S. (1956). *When Prophecy Fails: A Social and Psychological Study of a Modern Group that Predicted the Destruction of the World*. University of Minnesota Press.

Festinger, L. (1957). *A theory of cognitive dissonance*. Stanford, CA: Stanford University Press.

Festinger, L., & Carlsmith, J.M. (1959). Cognitive consequences of forced compliance. *Journal of Abnormal and Social Psychology, 58,* 203–210.

Frey, D., Irle, M., Möntmann, V., Kumpf, M., Ochsmann, R., & Sauer, C. (1982). Cognitive dissonance: Experiments and theory. In M. Irle (Ed.), *Studies in decision making* (pp. 281–310). Berlin: de Gruyter.

Gehring, W.J., Goss, B., Coles, M.G.H., Meyer, D.E.,& Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science, 4,* 385–390.

Gevins, A. S., Bressler, S. L., Morgan, N. H., Cutillo, B. A., White, R. M., Greer, D. S., & Illes, J. (1989). Event-related covariances during a bimanual visuomotor task. I. Methods and analysis of stimulus-and response-locked data. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 74*(1), 58-75.

Grent-'t'Jong, T., & Woldorff, M. G. (2007). Timing and sequence of brain activity in top-down control of visual-spatial attention. *PLoS Biol, 5*(1), e12.

Hanslmayr, S., Pastötter, B., Bäuml, K. H., Gruber, S., Wimber, M., & Klimesch, W. (2008). The electrophysiological dynamics of interference during the Stroop task. *Journal of Cognitive Neuroscience, 20*(2), 215-225.

Harmon-Jones, E. (2004). Contributions from research on anger and cognitive dissonance to understanding the motivational functions of asymmetrical frontal brain activity. *Biological Psychology, 67,* 51–76.

Harmon-Jones & Harmon-Jones (2007). Cognitive dissonance theory after 50 years of development. *Zeitschrift für Sozialpsychologie, 38*(1), 7-16.

Harmon-Jones, E., Harmon-Jones, C., Fearn, M., Sigelman, J. D., & Johnson, P. (2008). Left frontal cortical activation and spreading of alternatives: tests of the action-based model of dissonance. *Journal of Personality and Social Psychology, 94*(1), 1.

Harmon-Jones, E., Gerdjikov, T., & Harmon-Jones, E. (2008). The effect of induced compliance on relative left frontal cortical activity: A test of the action-based model of dissonance. *European Journal of Social Psychology, 38,* 35-45.

Hajcak, G., MacNamara, A., & Olvet, D. M. (2010). Event-related potentials, emotion, and emotion regulation: an integrative review. *Developmental neuropsychology, 35*(2), 129-155.

Izuma, K., Matsumoto, M., Murayama, K. (2010). Neural correlates of cognitive dissonance and choice induced preference change. *PNAS, 107*(51), 22014–22019.

Izuma, K., Akula, S., Murayama, K., Wu, D. A., Iacoboni, M., & Adolphs, R. (2015). A causal role for posterior medial frontal cortex in choice-induced preference change. *The Journal of Neuroscience, 35*(8), 3598-3606.

Jarcho, J. M., Berkman, E. T., & Lieberman, M. D. (2011). The neural basis of rationalization: cognitive dissonance reduction during decision-making. *Social Cognition and Affective Neuroscience, 6*, 460–467.

Kimel, S. Y., Lopez-Duran, N., & Kitayama, S. (2015). Physiological Correlates of Choice-Induced Dissonance: An Exploration of HPA-Axis Responses. *Journal of Behavioral Decision Making.* DOI: 10.1002/bdm.1845

Kitayama, S., Chua, H. F., Tompson, S., & Han, S. (2013). Neural mechanisms of dissonance: An fMRI investigation of choice justification. *Neuroimage, 69*, 206-212.

Larson, M. J., Kaufman, D. A., & Perlstein, W. M. (2009). Neural time course of conflict adaptation effects on the Stroop task. *Neuropsychologia, 47*(3), 663-670.

Lieberman M. D., Ochsner, K. N., Gilbert, D. T., Schacter, D. L. (2001). Do amnesics exhibit cognitive dissonance reduction? The role of explicit memory and attention in attitude change. *Psychological Science, 12,* 135–140.

Liotti, M., Woldorff, M. G., Perez, R., & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia, 38*(5), 701-711.

Luu, P., & Tucker, D. M. (2001). Regulating action: alternating activation of midline frontal and motor cortical networks. *Clinical Neurophysiology, 112*(7), 1295-1306.

Luu, P., Tucker, D. M., & Makeig, S. (2004). Frontal midline theta and the error-related negativity: neurophysiological mechanisms of action regulation. *Clinical Neurophysiology, 115*(8), 1821-1835.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288*(5472), 1835-1838.

Macdonald, J. S. P., Mathan, S., & Yeung, N. (2011). Trial-by-trial variations in subjective attentional state are reflected in ongoing prestimulus EEG alpha oscillations. *Frontiers in psychology, 2*, 82.

Makeig, S., Westerfield, M., Jung, T. P., Enghoff, S., Townsend, J., Courchesne, E., & Sejnowski, T. J. (2002). Dynamic brain sources of visual evoked responses. *Science, 295*(5555), 690-694.

Martinie, M. A., Olive, T., Milland, L., Joule, R. V., & Capa, R. L. (2013). Evidence that dissonance arousal is initially undifferentiated and only later labeled as negative. *Journal of Experimental Social Psychology, 49*(4), 767-770.

Mengarelli, F., Spoglianti, S., Avenanti, A., & di Pellegrino, G. (2015). Cathodal tDCS over the left prefrontal cortex diminishes choice-induced preference change. *Cerebral Cortex, 25*(5), 1219-1227.

Murray, A. A., Wood, J. M., & Lilienfeld, S. O. (2012). Psychopathic personality traits and cognitive dissonance: Individual differences in attitude change. *Journal of Research in Personality, 46*(5), 525-536.

Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P., & Kok, A. (2001). Error-related brain potentials are differentially related to awareness of response errors: Evidence from an antisaccade task. *Psychophysiology, 38*(5), 752-760.

Nigbur, R., Cohen, M. X., Ridderinkhof, K. R., & Stürmer, B. (2012). Theta dynamics reveal domain-specific control over stimulus and response conflict. *Journal of Cognitive Neuroscience, 24*(5), 1264-1274.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.M. (2011). FieldTrip: Open sources software for advanced analysis of MEG, EEG and invasive electrophysiological data. *Computational Intelligence and Neuroscience,* 2011, 1-9.

Orwell, G. (1949). *Nineteen Eighty-Four. A novel.* London: Secker & Warburg.

Ochsner, K. N., & Gross, J. J. (2005). The cognitive control of emotions. *Trends in Cognitive Sciences, 9,* 242–248.

Perlstein, W. M., Larson, M. J., Dotson, V. M., & Kelly, K. G. (2006). Temporal dissociation of components of cognitive control dysfunction in severe TBI: ERPs and the cued-Stroop task. *Neuropsychologia, 44*(2), 260-274.

Pfabigan, D. M., Seidel, E. M., Sladky, R., Hahn, A., Paul, K., Grahl, A., Küblböck, M., Kraus, C., Hummer, A., Kranz, G. S., Windischberger, C., Lanzenberger, R., & C. Lamma (2014). P300 amplitude variation is related to ventral striatum BOLD response during gain and loss anticipation: An EEG and fMRI experiment. *NeuroImage, 96*(100), 12-21.

Pogarell, O., Padberg, F., Karch, S., Segmiller, F., Juckel, G., Mulert, C., Hegerl, U., Tatsch, K., & Koch, W. (2011). Dopaminergic mechanisms of target detection—P300 event related potential and striatal dopamine. Psychiatry Research: *Neuroimaging, 194*(3), 212-218.

Price, D. D. (2000). Psychological and Neural Mechanisms of the Affective Dimension of Pain. *Science, 288*(5472), 1769–1772.

Qin, J., Kimel, S.Y., Kitayama, S., Wang, X., Yang, X., & Han, S. (2011). How choice modifies preference: Neural correlates of choice justification. *Neuroimage, 55*(1), 240–246.

Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science, 306*(5695), 443-447.

Sharot, T., De Martino, B., & Dolan, R. J. (2009). How choice reveals and shapes expected hedonic outcome. *The Journal of Neuroscience, 29*(12), 3760-3765.

Taake, I., Jaspers-Fayer, F., & Liotti, M. (2009). Early frontal responses elicited by physical threat words in an emotional Stroop task: Modulation by anxiety sensitivity. *Biological Psychology, 81*(1), 48-57.

Trujillo, L. T., & Allen, J. J. (2007). Theta EEG dynamics of the error-related negativity. Clinical *Neurophysiology, 118*(3), 645-668.

van Driel, J., Ridderinkhof, K. R., & Cohen, M. X. (2012). Not all errors are alike: theta and alpha EEG dynamics relate to differences in error-processing dynamics. *The Journal of Neuroscience, 32*(47), 16795-16806.

Van Veen, V., Krug, M. K., Schooler, J. W., & Carter, C. S. (2009). Neutral activity predicts attitude change in cognitive dissonance. *Nature Neuroscience, 12*(11), 1469-1474.

West, R. (2003). Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia, 41*(8), 1122-1135.

West, R., & Alain, C. (2000). Age-related decline in inhibitory control contributes to the increased Stroop effect observed in older adults. *Psychophysiology, 37*(02), 179-189.

Wu, Y., & Zhou, X. (2009). The P300 and reward valence, magnitude, and expectancy in outcome evaluation. *Brain research,* 1286, 114-122.

Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The neural basis of error detection: conflict monitoring and the error-related negativity. *Psychological review, 111*(4), 931.