Transcranial direct current stimulation and decision-making: the neuromodulation of cognitive reflection

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"Reason has built the modern world. It is a precious but also a fragile thing, which can be corroded by apparently harmless irrationality. We must favour verifiable evidence over private feeling."

Professor Richard Dawkins

"Science is a philosophy of discovery."

Professor Neil deGrasse Tyson

"The greatest danger facing us is ourselves – our irrational fear of the unknown. But there's no such thing as the unknown. Only things temporarily hidden, temporarily not understood."

Gene Roddenberry

Abstract

The ability to make judgements and decisions is crucial to our lives. The dual-process framework of judgement and decision-making (e.g. Stanovich, 2009) proposes that decisions are usually made using mental processes relying on automatic processes (called Type 1 processing) or on more controlled processes (called Type 2 processing). According to this theory, when we make a decision without conscious effort we rely on the autonomous processes of Type 1 intuitive thinking, which is prone towards errorful decision-making. Alternatively, if we use Type 2 thinking by committing cognitive resources (e.g., working memory) we engage analytic thinking by at least partly inhibiting Type 1 processing. The primary goal for this thesis is to test whether Type 1 versus Type 2 processes in decision-making can be linked to different neural substrates. Transcranial direct current stimulation (tDCS), a non-invasive method for enhancing or decreasing cortical excitability was used. Participants completed decision-making tasks (e.g., Cognitive Reflection Test (CRT), syllogistic reasoning) to capture performance indicating Type 1 or Type 2 processing, and executive function tasks to assess the basis of Type 1 and Type 2 processing. First, a meta-analysis was performed on a variety of experiments using tDCS, finding evidence for the involvement of frontal structures in judgement and decision-making. In subsequent experiments stimulation of the right but not left dorsolateral prefrontal cortex (DLPFC) with anodal tDCS increased performance compared to sham in the CRT and solving vignettes measuring heuristic thinking. In experiment three there was a cumulative effect of neuromodulation on Type 2 processing, with an increase in reflective thinking performance following each of two stimulation sessions. Individual differences in thinking dispositions and cognitive ability could not explain the results, and there were no performance-enhancing effects of stimulation on syllogisms or executive functions. These experiments provide evidence for the involvement of the right DLPFC in decision-making which relies on the inhibition of pre-potent responses (e.g., the CRT).

Originality statement

'I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UEL or any other educational institution, except where due acknowledgement is made in this thesis. Any contribution made to the research by others, with whom I have worked at UEL or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.'

Signed……………………..………………………………………………………………

Date…30/07/2019….………………………………………………………………

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Acknowledgements

This thesis is a culmination of three long years of research. During these years I have had the opportunity to combine two extensive corpora of research: judgement and decision-making (from cognitive psychology) and neuromodulation (from cognitive neuroscience). This is a personal achievement and milestone that started many years ago in school when I was introduced to the sciences.

First of all, my gratitude goes to the University of East London (UEL) Excellence Scholarship scheme for funding these years of research. All the preparation for the PhD interview in London, many years ago paid off when it was just the start of this three-year journey.

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Chapter 1 – Introduction and overview of chapters

1.1 Cognitive processes in judgement and decision-making

In recent decades an extensive field of research has emerged exploring the idea of the duality of mind in judgement and decision-making (JDM) (Stanovich & West, 1998; Kahneman, 2011). Starting in the early 1970s, Daniel Kahneman and Amos Tversky examined mental short-cuts, known as heuristics, during judgement and decision-making. They suggested that the use of heuristics led to systematic deviations from normative correct answers, called judgement and decision-making biases (Kahneman, 2011).

According to Kahneman and Tversky people often answered a difficult question (e.g., *Consider the letter R, in the English language is R more likely to appear in ... (a) the first position? Or (b) the third position?*) with a simpler one. (Tversky & Kahneman, 1973). In the case of thinking about the position of the letter R it is easier to think of examples of this letter appearing in the first position (*Can I think of more example of the letter R appearing in the first position?*) than the third position – Kahneman and Tversky called this the availability heuristic (Tversky & Kahneman, 1973).

The research on heuristics and biases made an important contribution to the idea of how we can understand intuitive processing of information when making a decision (Evans, 2003; Toplak, West, & Stanovich, 2011). Kahneman was awarded the 2002 Nobel Memorial Prize in Economic Sciences for investigating how these short-cuts influence decision-making in economics and finance. Fifteen years later in 2017, Richard Thaler, another decision-making scholar and economist won the Nobel Memorial Prize in Economic Sciences for his work that included ‘nudging’ – the alteration of ‘choice architectures’ (i.e., how a choice is presented) to promote better decision-making. Both Nobel laureates have made important contributions to the expanding field of decision-making. The fact that these Nobel prizes have been awarded to Kahneman and Thaler highlights the importance of examining how we make decisions. This thesis examines the neural correlates of decision-making by using non-invasive techniques of brain stimulation.

1.2 Non-invasive brain stimulation techniques

In Chapter 2, non-invasive brain stimulation techniques (NIBS) are reviewed in detail. These techniques offer the possibility to induce temporary cortical excitability alterations in localised brain areas (Nitsche & Paulus, 2000; Priori, 2003). By shifting cortical excitability these non-invasive techniques cause small neuroplastic changes in the anatomical region of interest. Since neuroplastic changes are crucial for memory, learning and higher-order cognitive functions researchers use the temporary window of change from the norm to investigate the causal involvement of a brain region in cognition or behaviour.

Transcranial direct current stimulation (tDCS) is a method by which alterations in cortical excitability are utilised in the laboratory setting on typical, healthy participants (Nitsche & Paulus, 2000; Priori, 2003). In 2001, Nitsche and Paulus demonstrated that the application of an electrical current to the motor cortex has a prolonged aftereffect on cortical excitability. The use of tDCS involves the application of a weak electrical current for a short duration of twenty minutes or less (Fritsch et al., 2010; Bikson et al., 2016). The current passes through the scalp to alter the cortical excitability of the target brain region. In cognitive research tDCS has been used to investigate the neural correlates of language function (Flöel, Rösser, Michka, Knecht, & Breitenstein, 2008; Liuzzi et al., 2010), memory (Utz, Dimova, Oppenländer, & Kerkhoff, 2010; Hill, Fitzgerald, & Hoy, 2016), language acquisition (Flöel et al., 2008; Liuzzi et al., 2010) and attention (Weiss & Lavidor, 2012; Reteig, Talsma, van Schouwenburg, & Slagter, 2017).

1.3 Review of judgement and decision-making literature

In Chapter 3 research on judgement and decision-making is reviewed. Here decision-making is defined within a dual-process framework of human thinking (Evans, 1984; Stanovich & West, 1998). Dual-process theories posit that there are two qualitatively different types of processing that underlie human judgement and decision-making: intuitive (Type 1) and analytic (Type 2) processes. In the case of the frequency of the position of the letter R in words, Type 1 processing results in an intuitive solution that relies on the availability heuristic by using easily thought of examples of words starting with the letter R, whilst Type 2 processing considers examples of the R appearing in the third position before arriving at a solution (Tversky & Kahneman, 1973).

Type 1 decision-making is associated with automatic responses (Evans, 2003) and high impulsivity (Strack & Deutsch, 2004) that use mental short-cuts (e.g., heuristics). Type 1 processing is usually associated with more errorful, biased outcomes (Evans, 2003). Type 2 thinking, however, is proposed to be a more controlled type of processing and requires the use of effortful mental operations (Schneider & Shiffrin, 1977; Kahneman, Krueger, Schkade, Schwarz, & Stone, 2006). Crucially, for normatively correct judgement and decision outcomes Type 2 processing is thought to largely inhibit Type 1 processing (Evans, 2012).

It is important to investigate and understand the cognitive and neurophysiological aspects of decision-making, two of the reasons are that: (i) understanding whether the important claims of qualitatively different higher processes in the brain can be substantiated, and (ii) decision-making is a crucial aspect of our cognition with wide social relevance. Sub-optimal, incorrect decision-making, when not corrected by Type 2 processing can result in poor decision-making with consequences for finance (Hedesström, Svedsäter, & Gärling, 2007; Thoma, White, Panigrahi, Strowger, & Anderson, 2015), health (Scheibehenne, Miesler, & Todd, 2007; Pachur, Hertwig, & Steinmann, 2012) and even politics (Selb, 2008; Nisbet, 2009).

1.4 Current understanding of the neurobiology of decision-making

In Chapter 4, the neurophysiology of judgement and decision-making is reviewed in detail. The current understanding of the neurophysiology of decision-making is informed by functional neuroimaging research (Ernst & Paulus, 2005; Kable & Glimcher, 2009). Much of the research is concerned with the investigation of subjective valuation (Neumann & Morgenstern, 1944; Kable & Glimcher, 2009) and forecasting

(Delgado, 2007). For the purposes of this PhD research, the neurophysiology of executive functioning is more applicable because impulsivity control (Evans & Curtis-Holmes, 2005) and set-shifting (Toplak et al., 2011) are crucial components of dual-process decision-making (Evans & Curtis-Holmes, 2005; Stanovich, 2009).

The brain region of interest for executive functioning in decision-making is the dorsolateral prefrontal cortex (DLPFC), an area that has been reliably linked to decision-making (Dockery, Hueckel-Weng, Birbaumer, & Plewnia, 2009; Tayeb & Lavidor, 2016). The left DLPFC is involved in affective modulation (Hare, Camerer, & Rangel, 2009), attentional processing (Goel et al., 2006) and self-regulation (Mengarelli, Spoglianti, Avenanti, & Di Pellegrino, 2015), whilst the right DLPFC has a role in set-shifting (i.e., the ability to move from one mental simulation to another) (Loftus, Yalcin, Baughman, Vanman, & Hagger, 2015) and impulsivity control (Loftus et al., 2015).

Direct current neuromodulation has been used successfully to investigate the neural substrates of executive functioning (Weiss & Lavidor, 2012; Tayeb & Lavidor, 2016). Some executive functions are crucial aspects of the dual-processing framework of judgement and decision-making (Miyake et al., 2000; Evans, 2008). Among the executive functions that have been investigated in the tDCS literature are attention (Weiss & Lavidor, 2012; Reteig et al., 2017), set-shifting (Strobach, Antonenko, Schindler, Flöel, & Schubert, 2016; Tayeb & Lavidor, 2016), and response inhibition (Li, Huang, Constable, & Sinha, 2006; Jacobson, Javitt, & Lavidor, 2011). The successful application of tDCS as a tool for investigating the neural correlates of executive functions, and the association between executive functions and judgement and decision-making suggests that tDCS can be a useful tool for examining the neurophysiology of judgement and decision-making.

1.5 Focus, scope of research and research objectives

This PhD thesis has applied tDCS as a technique to investigate the neural substrates of the dual-process framework of judgement and decision-making. The neuromodulation is used online (i.e., during behavioural testing) in Experiment 1 (Chapter 5) and offline (i.e., before behavioural testing) in Experiments 2 and 3 (Chapters 6 and 7) to examine any differences that these neuromodulatory modes have on judgement and decision-making.

This research assesses the effects that tDCS has on the neural substrates of decision-making tasks that vary in executive function requirements, for example the Cognitive Reflection Test (CRT) which taps inhibitory control whilst syllogistic reasoning does not. Furthermore, working memory and inhibition tasks are examined.

Research questions

The specific questions to be addressed by this research are:

1. Does neuromodulation of the frontal brain areas (specifically the DLPFC) affect judgement and decision-making performance?

2. Does stimulating different regions in the prefrontal cortex (specifically the DLPFC) differentially modulate performance in tasks associated with Type 1 and Type 2 (executive function tasks)?

3. What is the relationship between executive functions (e.g. updating, inhibition) and Type 2 thinking performance?

4. What is the nature of the interaction between Type 1 and Type 2 processing in the dual-processes framework of judgement and decision-making?

Existing concepts and models of judgement and decision-making are examined throughout this body of research.

Chapter 2 – Review of tDCS

On transcranial direct current stimulation: principles, physiological mechanisms and effects on cognition – a literature review

2.1 Background of tDCS

This method is a safe, cost-effective, non-invasive neuromodulatory technique that is characterised by the application a weak direct electrical current through the scalp (Nitsche & Paulus, 2000; Priori, 2003). The use of a direct current to modulate cortical excitability was first described in the invasive, clinical literature for the treatment of presurgical epilepsy (Dymond, Coger, & Serafetinides, 1975). In the research literature, the effects of a non-invasive direct current were first described in a study of the after-effects of the application of direct current through the motor cortex (Nitsche & Paulus, 2000).

Since the reintroduction of tDCS as a technique for the investigation of neurological processes, tDCS has been used to modulate cognition functions that include working memory (Utz et al., 2010; Hill et al., 2016), language acquisition (Flöel et al., 2008; Liuzzi et al., 2010), planning (Dockery et al., 2009), set-shifting (Strobach et al., 2016; Tayeb & Lavidor, 2016), attention (Weiss & Lavidor, 2012; Reteig et al., 2017), response inhibition (Li et al., 2006; Jacobson et al., 2011), and visual cognition (Barbieri, Negrini, Nitsche, & Rivolta, 2016; Costantino, Bossi, Premoli, Nitsche, & Rivolta, 2017). In clinical research, tDCS has been successfully used to alter motor function in stroke (Hummel et al., 2005; Boggio et al., 2007) and Parkinson's disease patients (Benninger et al., 2010; Kaski, Allum, Bronstein, & Dominguez, 2014), cognitive deficits in schizophrenic (Vercammen et al., 2011; Hoy, Arnold, Emonson, Daskalakis, & Fitzgerald, 2014) and Parkinson's Disease patients (Leite, Gonçalves, & Carvalho, 2014; Manenti et al., 2016), and addiction (Feil & Zangen, 2010; den Uyl, Gladwin, & Wiers, 2015).

2.2 Physiological background of tDCS: mechanisms of action

In the typical setup the direct current is delivered through a pair of rubber electrodes that are encased within sponges. The sponges are moistened with a contact media that is either tap water (Palm et al., 2014), deionised water (DaSilva, Volz, Bikson, & Fregni, 2011), an electrolyte-based gel (Woods et al., 2016) or sodium chloride (NaCl) saline solution (Dundas, Thickbroom, & Mastaglia, 2007). The moistening of the sponges minimizes any discomfort from the stimulation, reduces resistance to the current and improves the homogeneity of the electric field under the electrodes (Nitsche et al., 2008). Oversaturation of the sponges with a contact media undermines the reproducibility and effectiveness of the tDCS so care must be taken when preparing the electrodes (Woods et al., 2016).

The primary effect of direct current on neurons is the alteration of resting membrane potentials towards hyperpolarisation or depolarization (Bindman, Lippold, & Redfearn, 1962; Reinhart, Cosman, Fukuda, & Woodman, 2017). The polarization depends on the direction of the flow of current relative to axonal orientation (Bikson & Rahman, 2013; Lefaucheur et al., 2017). With a few exceptions, when direct current is delivered to the dorsolateral prefrontal cortices (DLPFC) anodal tDCS increases cortical excitability (Georgii, Goldhofer, Meule, Richard, & Blechert, 2017), whilst cathodal tDCS decreases cortical excitability (Zmigrod, Zmigrod, & Hommel, 2016). In a few exceptions, anodal tDCS has been reported to decrease excitability (Monte-Silva et al., 2013; Pelletier & Cicchetti, 2015), and cathodal tDCS increase excitability (Batsikadze, Moliadze, Paulus, Kuo, & Nitsche, 2013; Pirulli, Fertonani, & Miniussi, 2014). Variance in brain morphology at stimulation sites (e.g., neuronal density) (Laakso, Tanaka, Koyama, De Santis, & Hirata, 2015), individual differences in skull thickness (Horvath, Forte, & Carter, 2015a) and hair thickness (Horvath, Carter, & Forte, 2014) may account for the difference in the effects of stimulation across studies.

2.2.1 Physiological mechanisms during tDCS (i.e., online)

When a direct current is applied to the cortex through the use of online neuromodulation (i.e., stimulation during behavioural testing) the current preferentially modulates neuronal networks that are already activated by inducing a change in electrical activity in the neurons within this network (Coffman et al., 2012; Bikson & Rahman, 2013). For example, when an individual is asked to attend to an object in a visual search task anodal neuromodulation of the left dorsolateral prefrontal cortex can boost attention by decreasing the ability to shift from local-to-global features (Coffman, Clark, & Parasuraman, 2014).

2.2.2 Physiological mechanisms after tDCS (i.e., offline)

When a direct current is applied prior to behavioural testing (i.e., offline neuromodulation) the neuromodulatory effects can last up to an hour after the cessation of stimulation (Priori, 2003). Any changes in behavioural results (e.g., working memory capacity) from testing during the hour after stimulation, compared to sham, can be associated with the aftereffects of stimulated area of the cortex. For example, offline stimulation can affect reaction time and accuracy in the 2-back variation of the n-back (Hoy et al., 2013). Furthermore, Hoy and colleagues (2013) reported that the behavioural effects of offline stimulation varied depending on the time of testing after stimulation. Reaction times on the 2-back decreased over time from 592ms immediately after stimulation to 523ms at 40 minutes after stimulation.

2.2.3 Physiological mechanisms of multiple sessions of tDCS

Multiple sessions of low intensity anodal direct current show a cumulative effect on cortical excitability after repeated daily sessions (Alonzo, Brassil, Taylor, Martin, & Loo, 2012; Martin, Liu, Alonzo, Green, & Loo, 2014). The cumulative effects of direct current have been used for the treatment of neuropsychiatric conditions that include depression (Liebetanz et al., 2006; Mutz, Edgcumbe, Brunoni, & Fu, 2018) and eating disorders (Ljubisavljevic, Maxood, Bjekic, Oommen, & Nagelkerke, 2016).

In healthy participants, multiple sessions of direct current stimulation have demonstrated a cumulative and additive increase in motor cortex excitability

(Ammann, Lindquist, & Celnik, 2017). When anodal direct current is applied to the left dorsolateral prefrontal cortex in two daily sessions an enhancement in skill acquisition in cognition have been demonstrated (Martin et al., 2014). One explanation for the improvement in skill acquisition is that the repeated practice of a given task makes the task easier overtime through the practice effect (Donovan & Radosevich, 1999), whilst the direct current when applied to the relevant cortical network enhances cortical excitability (Martin et al., 2014). Paired together the practice effect and increased cortical excitability produces the enhanced effects on cognition from the multiple sessions of tDCS (Martin et al., 2014).

2.3 Electrode positions, polarity and individual differences in tDCS influence

The cellular influence of direct current on the brain depends on the distance and orientation of the axonal axes with respect to the electric field (Das, Holland, Frens, & Donchin, 2016; Fertonani & Miniussi, 2017). A minimum of two electrodes must be used in order to generate an electric field that can modulate neuronal excitability (see Figure 2.1). When a positive site electrode (the anode) is positioned opposite a negative site electrode (the cathode) the direct current is produced when weak constant current flows from the positive electrode to the negative electrode (Purpura & McMurtry, 1965; Stagg & Nitsche, 2011).

In tDCS experiments, the stimulating electrode which is placed over the site of interest can be either anodal or cathodal depending on the direction of polarity between electrodes (Parazzini, Rossi, Rossi, Priori, & Ravazzani, 2013; Coffman et al., 2014). The second electrode that is at the site that is of no interest to researchers (called the return or reference electrode) can be positioned on a part of the body that is far from the brain, e.g., the shoulder (Parazzini et al., 2013; Ferrucci, Cortese, & Priori, 2015) or wrist (Tremblay, Beaulé, Lepage, & Théoret, 2013; Fertonani & Miniussi, 2017).

Anodal tDCS increases neuronal excitability (Das et al., 2016), whilst cathodal tDCS deceases neuronal excitability (Pirulli et al., 2014). A third type of stimulation, sham stimulation causes a slight tingling sensation under the electrodes with the aim of preventing participants from differentiating between active and sham. Crucially, sham does not affect cortical excitability (unlike active stimulation), as it ceases after a short time without increasing or decreasing neuronal excitability (Ambrus et al., 2012; Georgii et al., 2017). Sham stimulation is the equivalent of a control condition in the psychological literature (Gandiga, Hummel, & Cohen, 2006). After the behavioural task is performed the results can be compared with either baseline data (Jones, Peterson, Blacker, & Berryhill, 2017) or sham stimulation data (Woods et al., 2016).

The behavioural effects of anodal and cathodal direct current stimulation are not always linear, as many factors are known to influence the outcome of direct current stimulation. The actions of a participant whilst they are waiting for the completion of the stimulation can directly produce cognitive interference in offline studies by activating neuronal networks which are consequently influenced by the direct current (Hsu, Tseng, Liang, Cheng, & Juan, 2014; Bortoletto, Pellicciari, Rodella, & Miniussi, 2015; Antal et al., 2017). Other inter-individual variables that can influence direct current include cranial anatomy (e.g., head size, brain lesions), brain morphology, baseline behavioural states, neurochemistry, hormones, sex, genetics, handedness, age and medication (Das et al., 2016; Hsu, Juan, & Tseng, 2016).

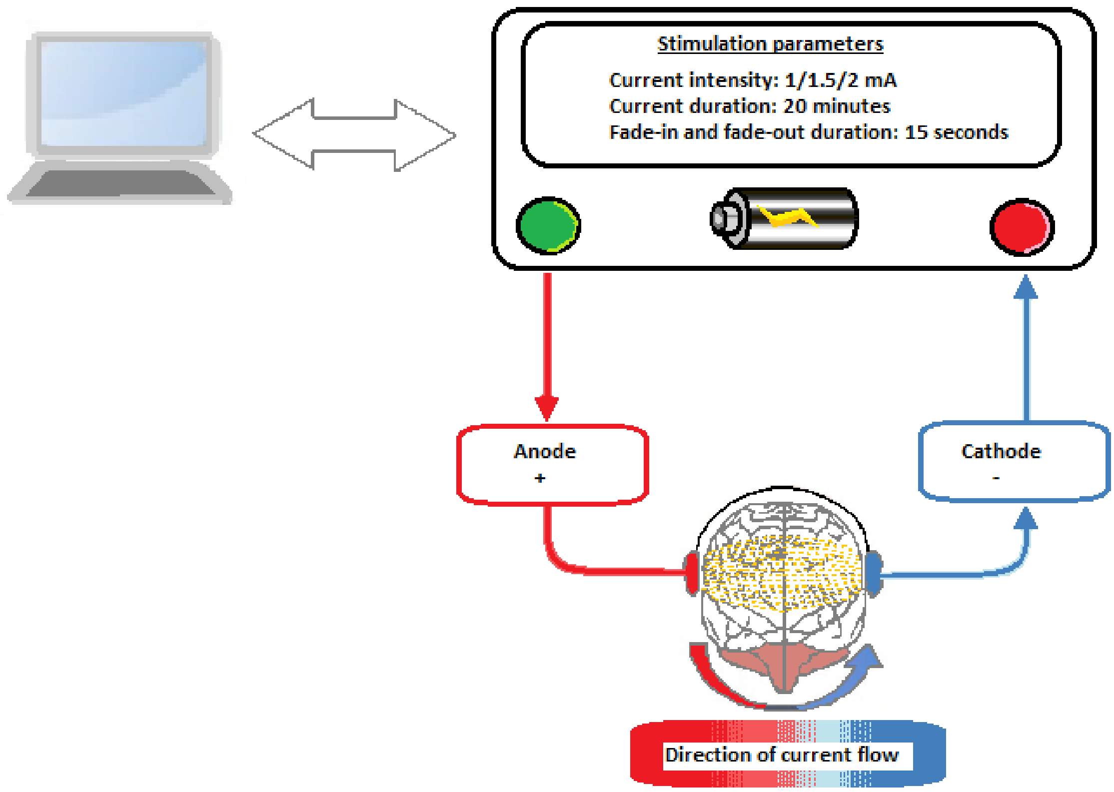


Figure 2.1. The direction of current flow (polarity) from the anode (positive electrode) to the cathode (negative electrode) within a typical two-electrode tDCS set-up.

2.4 Current intensity and current density

The intensity of tDCS refers to the steady-state strength of the direct current (measured in mA) that is applied to the anode electrode or cathode electrode depending on whether the experimenter wants to increase or decrease cortical excitability (Bikson et al., 2016). When multiple electrodes are used, the current intensity is the sum of the current across all electrodes (Nitsche & Paulus, 2000; Tang, Hammond, & Badcock, 2016).

The current density of tDCS refers to degree of compactness of the current intensity in a given area. Current density (mA/cm^2) can be calculated by dividing the current intensity (mA) by the electrode size (cm^2) (see Figure 2.2 below). Determining the current density at the targeted brain region is crucial for predicting stimulation efficacy (Miranda, Lomarev, & Hallett, 2006). Larger current densities result in stronger effects of tDCS compared to low current densities (Nitsche et al., 2008; Woods et al., 2016). Figures 2.2 and 2.3 shows the current density that can be predicted from different current intensities and electrode sizes.

$$Current\ density = \frac{Current\ intensity\ (mA)}{Electrode\ size\ (cm^2)}$$

Figure 2.2. The equation for calculating current density from current intensity and electrode size.

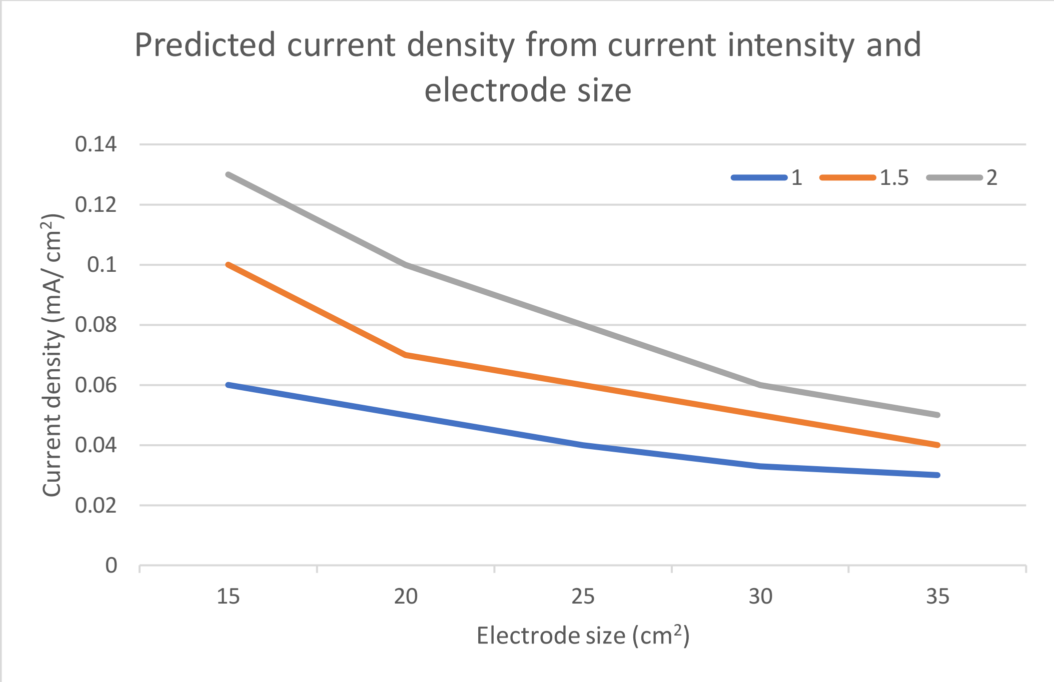


Figure 2.3. The predicted current density (mA/cm^2) from electrode size (cm^2) and current intensity (mA).

2.5 Duration of stimulation and duration of after-effects

The direct current stimulation duration influences the extent to which cortical activity is modulated by the weak electrical current (Ohn et al., 2008; Cuypers et al., 2013). A minimum stimulation duration of 7 minutes is required to induce a notable change in cortical excitability (Fritsch et al., 2010; Bikson et al., 2016). The upper end of stimulation duration in the tDCS literature is twenty-five minutes (Lefaucheur et al., 2017). The average duration that a direct current stimulation is applied for in the literature is between twenty and twenty-five minutes (Nitsche et al., 2008).

Direct current stimulation of 9 to 13 minutes has a neuromodulatory after-effect of an hour, whilst twenty-minutes of stimulation can have lasting after-effects for over an hour (Nitsche & Paulus, 2000; Priori, 2003; Nasseri, Nitsche, & Ekhtiari, 2015). The after-effects of stimulation remain whilst the heightened (anodal stimulation) or lowered (cathodal stimulation) cortical excitability gradually return to baseline levels in the minutes after neuromodulation (Peterchev et al., 2012).

The short-lived after-effects of a single session of direct current stimulation can be reinforced with the application of multiple sessions of tDCS (Reis et al., 2009; Vallence & Ridding, 2014). In healthy participants, multiple spaced sessions with an inter-session interval of less than 24 hours can increase the duration of the behavioural and cognitive effects of stimulation to several weeks (Reis et al., 2009; Vallence & Ridding, 2014) or months (Stagg & Nitsche, 2011; Molaee-Ardekani et al., 2013).

Chapter 3 – Judgement and decision-making review

On judgement, decision-making and the mechanisms beyond the dual-process framework, a literature review

3.1 Dual-process theories in decision-making

3.1.1 The history of dual-process theory

The distinction between two different types of judgement and decision-making processes has its origins in ancient Greece (Vaisey, 2008). Plato famously described emotion and reason as two horses trying to pull a chariot in opposite directions (Fugate, 2007; Bari & Robbins, 2013). In order to steer the chariot in the intended direction the charioteer must take control the horses. If the charioteer is pulled in the direction that either horse was pulling then this determines whether emotion or reason alone plays a crucial role in decision-making. This Platonic tradition of philosophy suggests that decisions are made by inferential, reflective thinking (the horse of reason) or intuitive thinking (the horse of emotion) (Croskerry, 2009).

The modern foundations of dual-process theory originated in the work of William James in his 1890 book: The Principles of Psychology (James, 2013). James suggested that there are two distinct types of reasoning: 'true reasoning' and associative reasoning. Associative reasoning is synonymous with inferential and intuitive thinking, whilst true reasoning is equivalent to reflective, and analytical thinking (Smith & DeCoster, 2000; Evans, 2008). Unlike Plato's allegory of the horses, James' theory was informed from the early of psychology rather than philosophy.

In 1973, Seymour Epstein published the Cognitive Experiential Self Theory (CEST) of personality building on eighty-three years of research in psychology since James' publication of The Principles of Psychology (Epstein, 1973; Novak & Hoffman, 2008). Epstein's dichotomous theory posits that individuals have the capacity to process information through either an experiential system (i.e., inferential and intuitive) or a rational system (i.e., reflective and analytical). The experiential system is influenced by affect (i.e., emotion), whilst the rational system relies on logical rule-based processes. It is from building on the CEST that Epstein developed the Rational Experiential Inventory (REI) which measures the precepts set-out in the CEST - this has become a highly cited tool in the decision-making literature with over 900 citations to date (Google Scholar, July, 2018) (Pacini & Epstein, 1999).

Evans' first dual-process theory of judgement and decision-making was published in 1984 (Evans, 1984; Stanovich & West, 1998). Evans' dichotomy distinguished between heuristic thinking (i.e., intuitive thinking) and analytic thinking. Heuristic thinking, meaning to discover without a guarantee of optimal decision-making, is responsible for the processing of the relevant information for a decision whilst ignoring non-important information. Analytic thinking is rule-based and operates by generating inferences from information (Evans, 2008). Evans' model differs from Epstein's CEST model in two ways: (i) it focuses on judgement and decision-making rather than personality, and (ii) it is a sequential rather parallel model – in sequential models intuitive thinking starts before analytic thinking, whilst in parallel models both processes begin at the same time (Epstein, 1973; Evans, 1984).

At about the same time as Epstein (Epstein, 1973) and Evans (Evans, 1984) began to work on judgement and decision-making, Daniel Kahneman and Amos Tversky started work on heuristics and biases (Kahneman & Tversky, 1972; Amos Tversky & Kahneman, 1973). Although there was no explicit discussion of a dual-process model in Kahneman and Tversky's early work in the 1970's, they examined some of the heuristics and biases that are used in intuitive thinking, also called decision-making biases or cognitive biases (Kahneman & Tversky, 1973; Amos Tversky & Kahneman, 1974). Kahneman's work established that individual's often make errors in decision-making by employing sub-optimal decision processes (i.e., heuristics) that result in decision-making biases. These decision-making biases fit into the dual-process dichotomy because when used without conscious effort these heuristics and biases have the potential to produce errorful decisions (Amos Tversky & Kahneman, 1973, 1974). When sufficient effort and cognitive resources are allocated to making a decision these biases can be avoided and the analytic processes employed (De Neys, 2012; Pennycook, Cheyne, Barr, Koehler, & Fugelsang, 2015).

In 2000, Stanovich and West coined the terms 'System 1' and 'System 2' to refer to the dual-processes of decision-making, these terms cleared up much of the confusion around what to call each of these processes (see Table 3.1). System 1 refers to the intuitive, automatic, and rapid decision-making process that is associated with heuristic use (Evans, 1984). System 2 is characterised by rule-based, reflective, analytic, and slow decision-making (Evans, 2008). These terms for the dual-processes have enabled researchers to publish their research in decision-making with relatively unified labels for these thinking processes. As of 2008 dual-process theorists have replaced the terms System 1 with 'Type 1' and System 2 with 'Type 2' after Evans suggested that the original terminology commits scholars to a two-system view (Evans, 2008). Stanovich and West support the change in terminology, noting that to use the labels Systems 1 and 2 connote that the two processes can be accurately mapped onto distinct corresponding brain systems which is not the case (Stanovich, West, & Toplak, 2011). Some researchers still use the terminology of System 1 and System 2 (Gervais & Norenzayan, 2012; Tay, Ryan, & Ryan, 2016). Evans argued that Type 2 processes require access to working memory capacity, whilst Type 1 processes do not, therefore these are not cognitive systems (Evans, 2008).

Table 3.1. A few examples of dual-process framework labels by publication

Literature reference	Type 1 label	Type 2 label
Epstein, (1973)	Experiential system	Rational system
Schneider & Shiffrin, (1977)	Automatic	Controlled
Evans, (1984)	Heuristic	Analytic
Stanovich & West, (2000)	System 1	System 2
Nisbett et al., (2001)	Holistic	Analytic
Krishna & Strack, (2017)	Impulsive	Reflective

Among the scholars of judgement and decision-making who support the dual-process framework there is disagreement about the exact nature of the framework (De Neys & Glumicic, 2008; Stupple & Ball, 2008) (Figure 3.1). Some of the scholars conceive of a dual-process framework in which intuitive, Type 1 processing and analytic, Type 2 processing begin at the same time, working in parallel until one of these processes produce a solution (Epstein, 1973; Sloman, 1996). On the other hand, other theorists posit that intuitive (Type 1) and analytic (Type 2) processes act sequentially (Evans, 1989; Thompson, 2009). The sequential theorists suggest that Type 1 processing begins before Type 2 processing with this latter taking over once the former has failed to produce a solution.

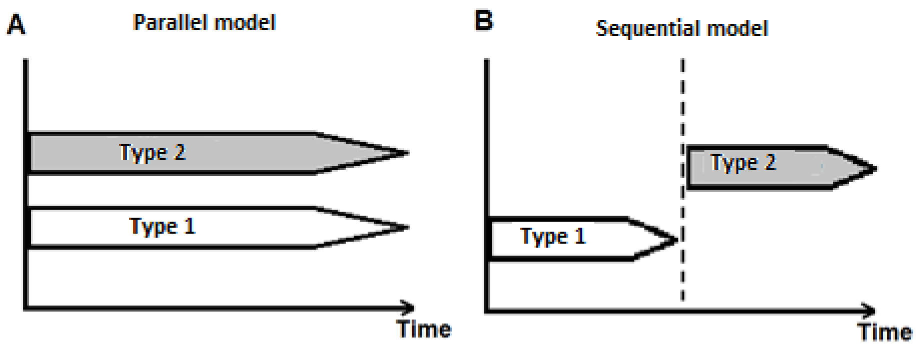


Figure 3.1. Parallel (panel A) and sequential (panel B) models of the dual-process framework of judgement and decision-making.

3.1.2 Parallel models of dual-process theory

Parallel models of dual-process decision-making posit that the Type 1 and Type 2 processes are in constant operation (Sladek, Phillips, & Bond, 2006). The Type 1 and Type 2 processes start at the same time, run in parallel, and operate in a 'first-past-the-post' race with the process that arrives first producing an answer. This can be illustrated with the following example of an incongruent base-rate vignette.

In a study of 1000 people, there were 5 engineers and 995 lawyers. Jack is a randomly chosen participant of this study. Jack is 36-years-old. He is not married and is somewhat introverted. He likes to spend his free time reading science fiction and writing computer programmes.

What is most likely?

a. *Jack is an engineer.*
b. *Jack is a lawyer.*

When this vignette is presented to an individual parallel models of dual-process theory posit that the Type 1 solution (*an engineer*) and the Type 2 solution (*a lawyer*) have the same potential of being reached. The intuitive, Type 1 solution relies on the stereotype of the occupation engineer (e.g., introverted and a fan of science fiction) whilst the analytic, Type 2 processing computes the probability of each occupation (e.g., there were 5 engineers and 995 lawyers).

The following sections describe variations of dual-process models that propose a parallel, sequential or hybrid operation of Type 1 and Type processing.

3.1.2.1 Epstein's (1973) Cognitive Experiential Self Theory (CEST)

The Cognitive Experiential Self Theory (CEST) of personality has been influential in the development of the Rational Experiential Inventory (REI), a measure of Type 1 and Type 2 usage (Pacini & Epstein, 1999). Epstein's CEST dichotomy posits that all information is processed by an experiential system that is effortless (Type 1) and a rational system that is affect-free, abstract and analytical (Type 2); these act in parallel (Novak & Hoffman, 2008). Epstein hypothesised that the analytic processes developed to operate in the medium of language (Epstein, 1973; Osman, 2004).

3.1.2.2 Sloman's (1996) dual-process theory

Sloman's dual-process theory focuses on the computational distinctions of the two processes of decision-making (Sloman, 1996; Osman, 2004). According to Sloman's model the first process, associative reasoning (Type 1), operates by drawing inferences from related information. The second process of decision-making (Type 2) is rule-based and operates by applying logical abstractions (i.e., rules) to a set premises about which a decision is required (Sloman, 1996; Smith & DeCoster, 2000). Both associative and rule-based processes start operating on the information at the same time.

3.1.3 Sequential models of dual-process theory

Sequential models of dual-process decision-making posit that information is processed by a Type 1 process prior to any Type 2 processing (Evans, 1989; Pennycook, Fugelsang, & Koehler, 2015). If intuitive, Type 1 decision-making cannot produce a solution then a conflict arises as a result of the uncertainty about the correct solution, at this point analytic Type 2 processing monitors and resolves the conflict. In the example of the incongruent base-rate vignette (i.e., engineer versus lawyer) both Type 1 (*an engineer*) and Type 2 (*a lawyer*) remain the same as the aforementioned. The key difference in the sequential models is that the conflict and state of uncertainty primes Type 2 processing to take over.

3.1.3.1 Evans' (1989) original heuristic-analytic theory

Evans' original heuristic-analytic theory posits that information is processed by Type 1 heuristic processes pre-consciously without the awareness of the individual (Evans, 1989; Osman, 2004) (Figure 3.2). The relevant representation and features of the information (e.g., a stereotype in a base-rate vignette) are selected and a response is inferred. Deliberate and conscious, Type 2 processing computes the information through logical analysis when an individual has sufficient experience with dealing with this type of logic. One of the key features of this model is that the Type 2, analytic function is dependent upon the context and an individual's experience with logic and reasoning, this explains why individuals who do not know how to solve a logic problem answer incorrectly (Evans, 2006).

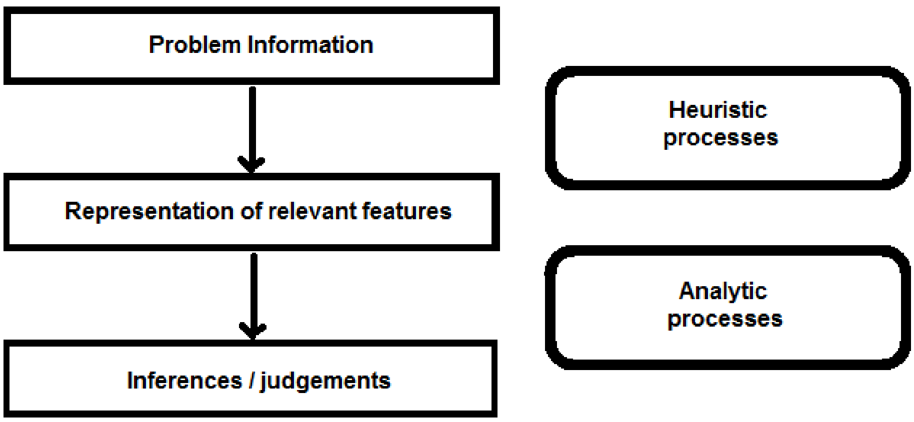


Figure 3.2. Evans' (1989) heuristic-analytic theory, figure adapted from cited article.

3.1.3.2 Thompson's (2009) metacognitive framework of reasoning

Thompson's (2009) metacognitive framework of reasoning emphasises that the outcome of reasoning is equally determined by the content of the information and the experience an individual has in processing this type of information (metacognition) (Figure 3.3). In this model the Type 1, heuristic process cues a response to information, if the response if fluent, familiar or consistent with metacognitive beliefs then it passes through the analytic Type 2 function with little or no processing. Alternatively, when the information does not cue a Type 1 response, it requires effortful processing, after which no response can be given (the give up function). With additional effort (requiring extra cognitive capacity) a reformatted piece of information can be resolve with a response that is consistent with Type 2 processing.

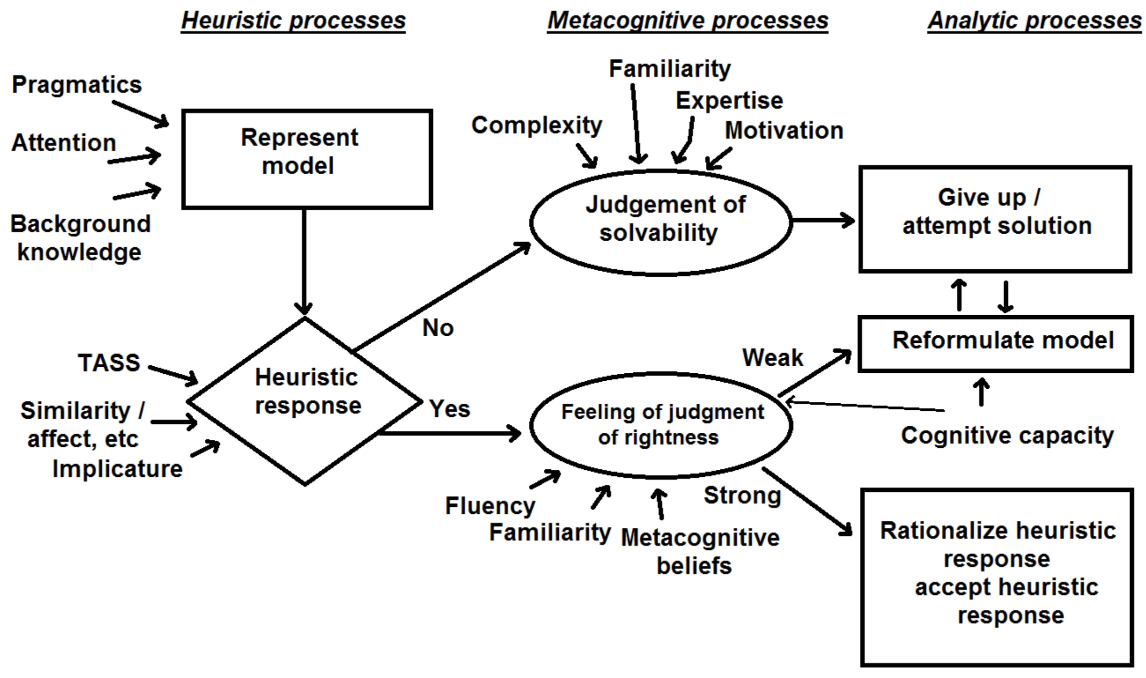


Figure 3.3. Thompson's (2009) metacognitive framework of reasoning. The acronym TASS stands for The Autonomous Set of Systems. Figure adapted from cited article.

3.1.3.3 De Neys' (2012) logical intuition model

De Neys' (2012) dual-process model emphasises reaction time, rather than accuracy as the main indicator of Type 1 or Type 2 use. He compares the sequential / serial (Figure 3.4 panel A) and parallel models (Figure 3.4 panel B) of judgement and decision-making and concludes that Type 1, intuitive processing can be split into two parts: heuristic intuition and logical intuition (Figure 3.4 panel C). Logical intuition differs from intuition because this refers to logical or probabilistic knowledge that is intuitive rather analytic. In this model reasoning based on the logical structure of an argument can be accomplished by logical intuition as rapidly as heuristic reasoning. Both logical intuition and heuristic intuition start processing information in parallel, once a conflict is detected between solutions produced by both forms of Type 1 processing, deliberate, Type 2 processing takes over. After the information is effortfully processed by Type 2 reasoning a correct solution is produced (De Neys, 2012; 2014).

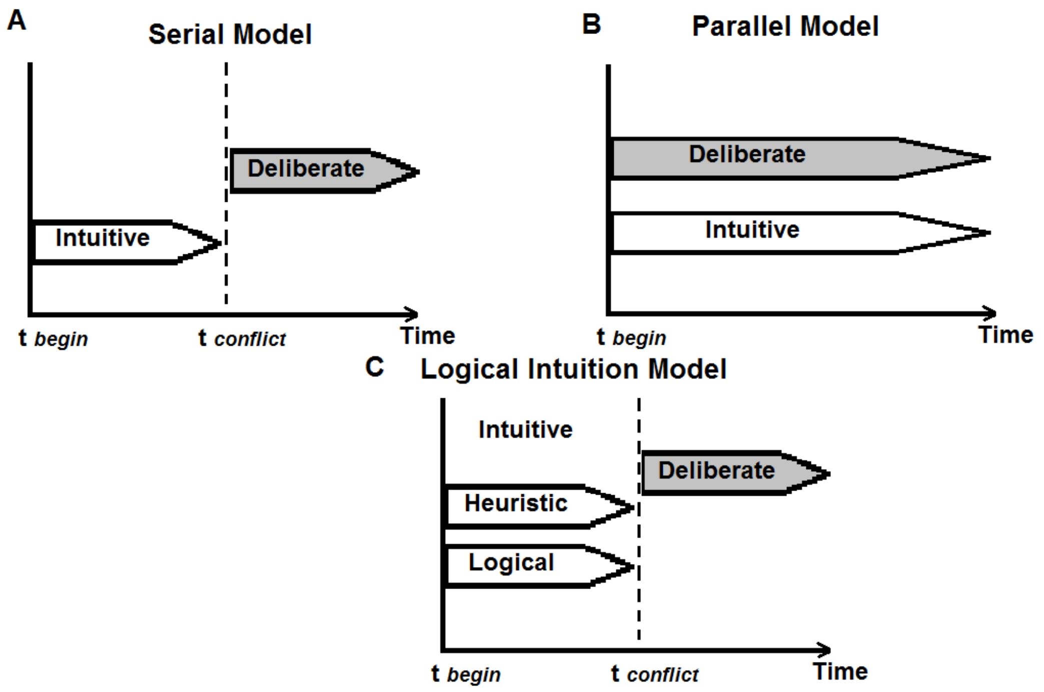


Figure 3.4. De Neys' (2012) logical intuition model of decision-making, figure adapted from cited article.

3.1.3.4 Pennycook's (2015) Three-stage dual-process model of analytic engagement

Pennycook, Fugelsang and Koehler's, (2015) three-stage dual-process model of analytic engagement emphasises that multiple conflicting solutions (i.e., initial responses - IR) can be cued from information during Type 1 processing and Type 2 processing (Figure 3.5). In stage 1, there may be more than one potential solution to a set of information. The multiple competing solutions (IRs) are initially processed by Type 1 thinking. For example, when an individual is confronted with an incongruent base-rate vignette (as in the engineer and lawyer example) two or more Type 1 solutions compete – *is Jack an engineer or perhaps a lawyer?* The second stage of the model monitors for these conflicting, and competing, Type 1 solutions in parallel. If there is no conflict, either due to an error in decision-making or because there is only one solution, the solution continues to stage 3 and is given as the answer (see the right-hand side of figure 3.5). Alternatively, Type 2 processing, acting as a monitor in the conflict detection function may detect a conflict and then begin Type 2 processing whereby the information continues to be processed through either the 'decouple' or 'rationalize' function. If the information continues to Type 2 processing through the rationalize function then one attempts to rationalize the solution that has made it this far, for example, *Jack must be an engineer because...* Alternatively, if the information continues through the (cognitive) decoupling function, then either (i) the solution is inhibited and replaced with a Type 2 solution (e.g., *the base-rate suggests Jack must be an lawyer, therefore he is a lawyer*), or (ii) if multiple solutions still exist then these are amalgamated into one solution (the alternative response - AR). Crucially, in the example of the base-rate vignettes amalgamation is not possible as all solutions are based on occupations (i.e., Jack cannot be an amalgamation of two occupations).

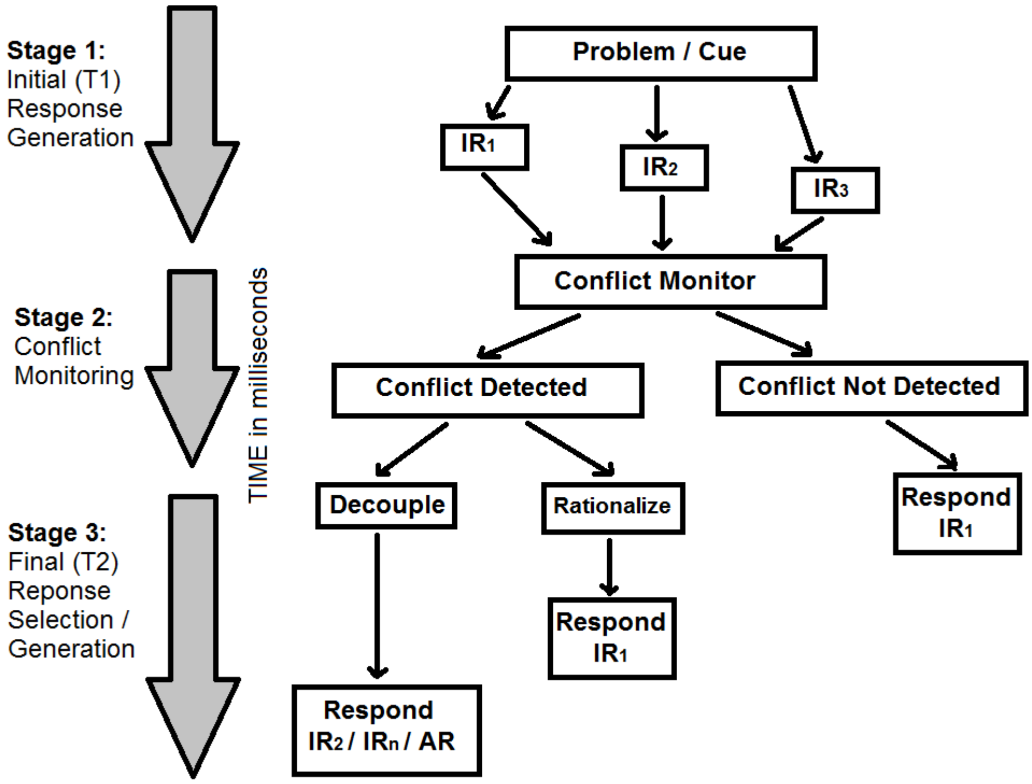


Figure 3.5. Pennycook's (2015) three-stage dual-process model of analytic engagement and decision-making, figure adapted from cited article. Abbreviations: Initial response (IR); alternative response (AR); Type 1 (T1) and Type 2 (T2).

3.1.4 Hybrid models of dual-process theory

Hybrid models combine elements of sequential and parallel model of dual-processing decision-making. Some of the hybrid models contain a feedback function so that information can be passed back through a previously used function (Evans, 2006), whilst other hybrid models distinguish between different forms of Type 2 reasoning (Stanovich, 2009). All hybrid models, like the parallel and sequential models, eventually produce the same response, they just differ in the route taken to produce the response.

3.1.4.1 Strack and Deutsch’s (2004) Reflective-impulsive model

Strack and Deutsch's (2004) reflective-impulsive model posits that decision-making, and social behaviour can be explained by the functions of reflective (Type 2) and impulsive (Type 1) processes (Figure 3.6). They proposed that Type 1 and Type 2 decisions (resulting in a behaviour) are processed through two different routes. An associative network (made of learned information) which can be strengthened and modified when new information is learned which is crucial to both Type 1 and Type 2 processes. The Type 1 response begins in the associative store which contains episodic links (i.e., links of the information to experience-based knowledge), and then passes directly to a behavioural schema function – a function for assessing whether a response is consistent with known behavioural schemas (i.e., how to act in a particular situation). If a Type 1 response matches a known behavioural schema then this response is given as a solution. Type 2 responses also originate in the associative store, they pass through a series of metacognitive and perceptual functions (*perception, referring, categorization and reasoning*) after which it arrives in the noetic decision function. In the noetic decision function, the response is compared with abstract, syllogistic rules where the information is compared to logical rules (e.g., is this syllogism logical valid or invalid?). After processing by the final metacognitive functions (*reasoning, behavioural decision and intending*) the response is passed through the behavioural schema function to be compared to known schemas and a Type 2 response is produced.

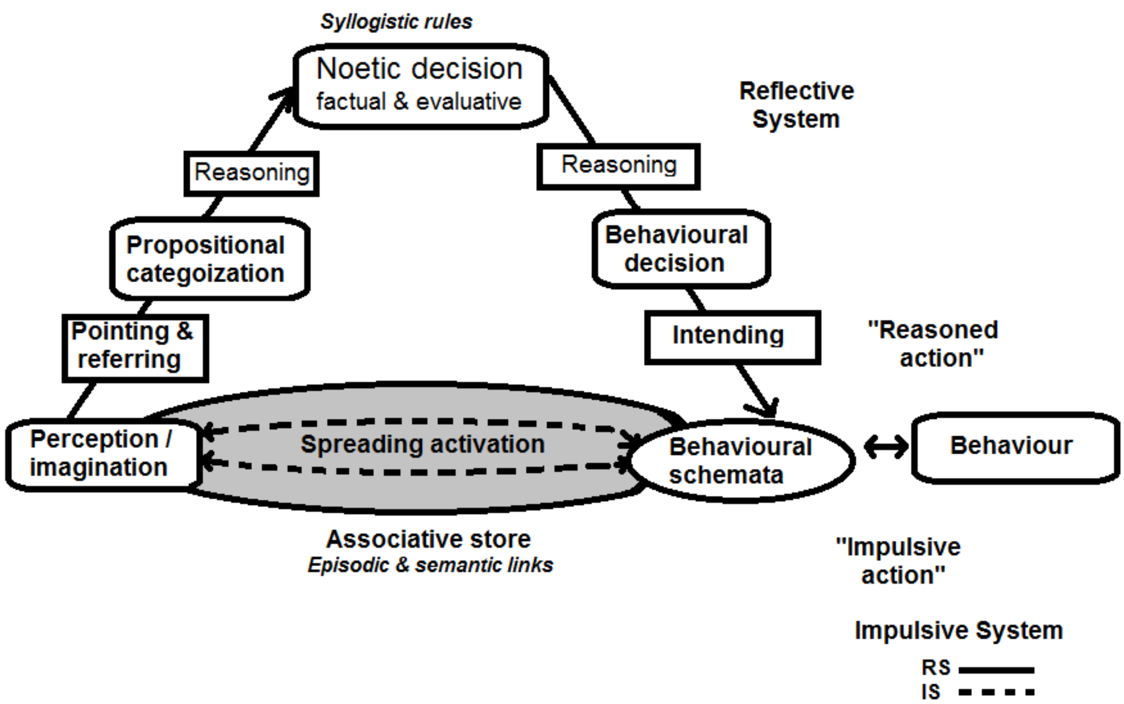


Figure 3.6. Strack and Deutsch's (2004) reflective-impulsive model of decision-making and behaviour, figure adapted from cited article. Abbreviations: RS, reflective system; IS, impulsive system.

3.1.4.2 Evans' (2006) Revised and extended heuristic-analytic theory model

Evans' (2006) revised and extended heuristic-analytic model builds on his 1989 heuristic-analytic model. The emphasis of this model is on hypothetical thinking (Figure 3.7). Evans suggests that to succeed in hypothetical thinking the reasoning must satisfy the three principles of hypothetical thinking (see Table 3.2): the singularity principle, relevance principle and satisficing principle. This model posits that Type 1 reasoning is the simplest form of decision-making. A Type 1 decision must satisfy three metacognitive functions (*task features, current goal and background knowledge*) before an error in the analytic Type 2 processes passes the response as a solution. Errors in Type 2 processing can occur through either time constraints (*time available*), insufficient cognitive ability (*general intelligence*) or a misunderstanding of instructions (*instructional set*). Evans emphasises that Type 1 reasoning is the default form of decision-making, whilst Type 2 responses are only produced after the construction of a relevant model in the analytic system. For the Type 2 response to be generated the information must pass through a satisfying function. When a model does not satisfy the function an evaluation the process starts over again.

Table 3.2. The three principles of hypothetical thinking as proposed by Evans, Over, and Handley (2003).

Principle	Explanation
Singularity	People consider a single mental model at a time
Relevance	People consider the most relevant model in the current context
Satisficing	Models are evaluated in the context of current goals and accepted if satisfying.

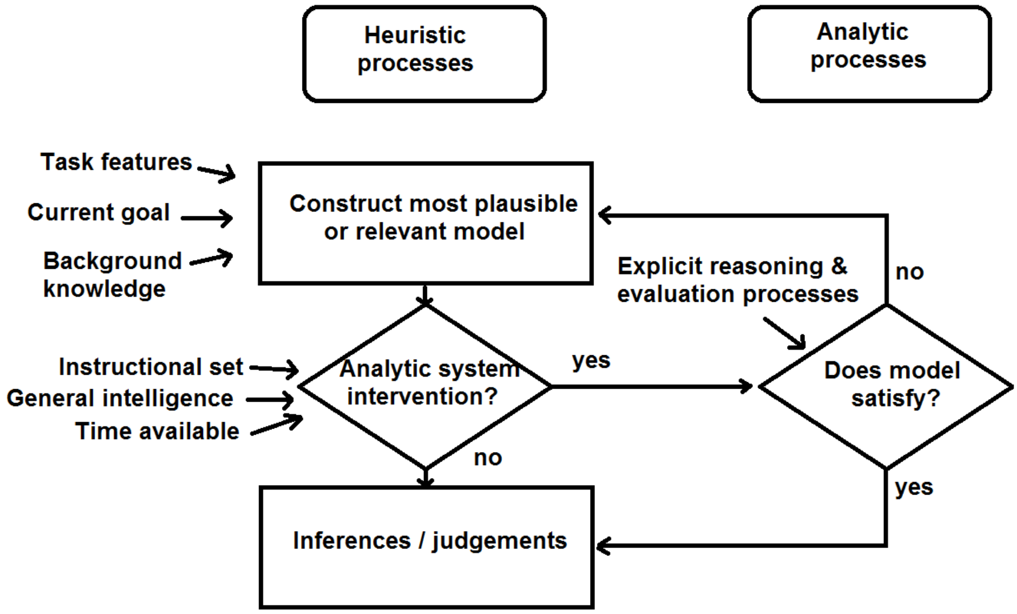


Figure 3.7. Evans' (2006) Revised and extended heuristic-analytic theory model, figure adapted from cited article.

3.1.4.3 Stanovich's (2009) Tripartite model

Stanovich's (2009) tripartite model is unique among the dual-process models because it distinguishes between two different sub-divisions of Type 2 reasoning: the reflective mind (thinking dispositions) and algorithmic mind (fluid intelligence) (Figure 3.8). This model posits that information is initially processed by Type 1 decision-making, also called The Autonomous Set of Systems and the Autonomous Mind (AM). This process can in some instances directly produce a response without going through Type 2 processing (the lowest route in Figure 3.8). Secondly, the information that originates in the AM goes on to be processed by the rule-based algorithmic mind where the response passes through a serial associative cognition function (analytic thinking without any hypothetical thinking) before arriving at a solution. Alternatively, after leaving the AM the information passes through the algorithmic mind, a cognitive simulation is produced (e.g., by imagining a scenario) before going on to the reflective mind. In the case of two individuals with similar algorithmic minds (e.g., fluid intelligence) a difference in solutions can result from difference at the reflective mind level (thinking dispositions). For example, if two individuals, with the identical scores on tests of fluid intelligence are given the same information they can produce different solutions because of variance in individual differences in rational thinking dispositions. In some cases, the variance in solutions from these two individuals could be corrected by further processing in the algorithmic mind to produce a normative Type 2 solution.

The results of the experiments in this thesis are discussed in detail in the context of Stanovich's tripartite model in Chapter 8. As this model specifically divides Type 2 processing into the 'reflective' and 'algorithmic' minds this has the potential to in part explain the effects of individual difference in thinking dispositions for judgement and decision-making.

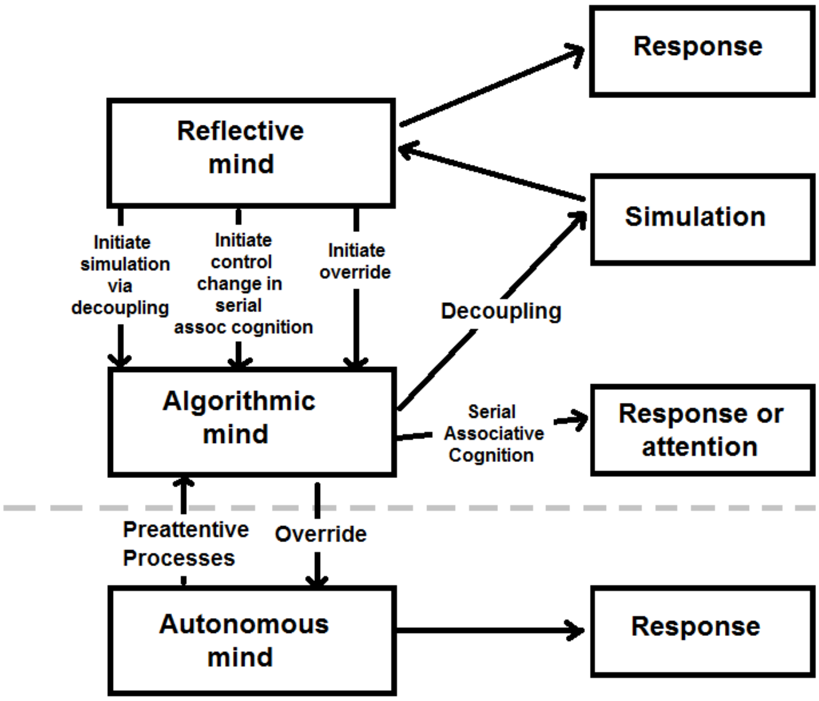


Figure 3.8. Stanovich's (2009) tripartite model of decision-making, figure adapted from cited article.

3.1.4.4 Handley and Trippas' (2015) dual-process model

Handley and Trippas' (2015) dual-process model of judgement and decision-making emphasises that individuals are intuitively sensitive to the logical structure of an argument (Figure 3.9). In this model time is represented from left to right. The length of the horizontal line indicates when an answer is available. Whether a logical problem is simple or complex, two Type 1 processes begin in parallel: a structure-based process (reliant on logic) and knowledge-based process (reliant on belief). For simple logical problems, a structure-based process is inhibited after a conflict between the two streams is detected to produce a Type 2 solution. In the case of complex logical problems, the knowledge-based process is inhibited to produce a Type 2 solution. It is at the time of conflict that either one of the Type 1 processes become consistent with Type 2 processing. Intuitive, errorful Type 1 solutions are produced when the incorrect Type 1 stream is inhibited.

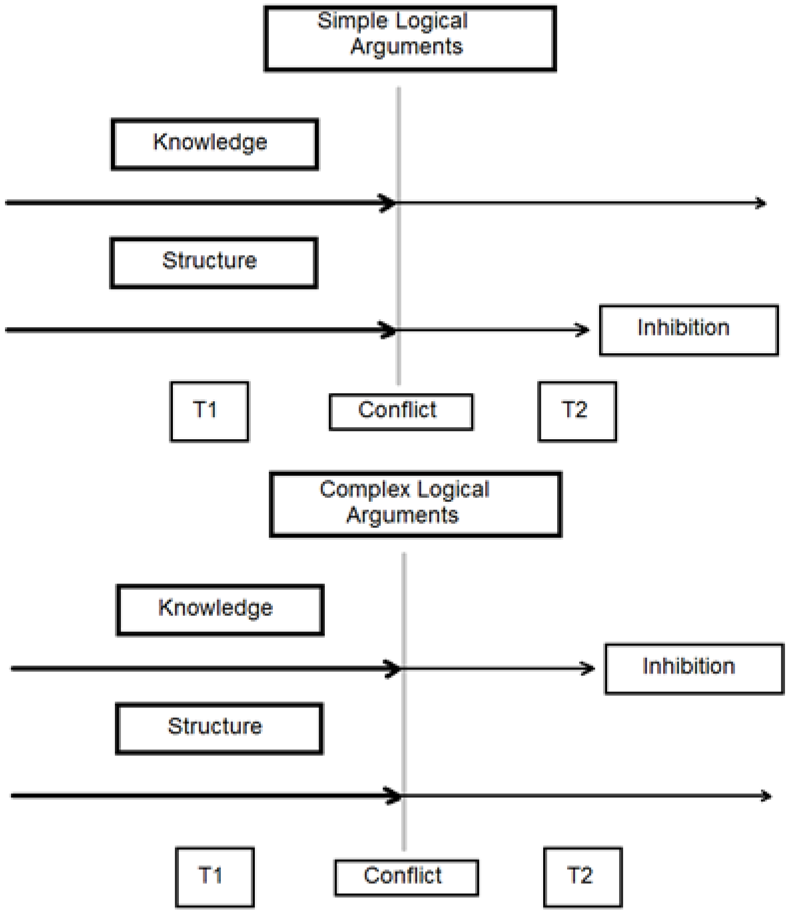


Figure 3.9. Handley and Trippas' (2015) dual-process model, figure adapted from cited article.

3.2 Cognitive executive functions and decision-making

Executive functions are a set of cognitive processes that are necessary for many cognitive tasks (Jurado & Rosselli, 2007; Chan, Shum, Toulopoulou, & Chen, 2008). At the basic level of cognition, they are responsible for the attentional control (Kane &

Engle, 2002; Schmeichel, 2007), inhibitory control (Diamond, 2013; Aron, Robbins, & Poldrack, 2014), working memory (updating) (Pennington, Bennetto, McAleer, & Roberts, 1996; St Clair-Thompson & Gathercole, 2006) and set-shifting (task switching / cognitive flexibility) (Monsell, 2003; Kiesel et al., 2010). At a higher level of cognition executive functions are crucial for planning (Lezak, 1982; Robbins, 1996), reasoning (Jurado & Rosselli, 2007; Diamond, 2013) and problem solving (Gilhooly & Fioratou, 2009; Wiley & Jarosz, 2012).

In the dual-process framework executive functions are key mechanisms to understand the relationship of intuitive, Type 1 and analytic, Type 2 processing (Barrett, Tugade, & Engle, 2004; Del Missier, Mäntylä, & Bruine de Bruin, 2010). Miyake and colleagues (Miyake et al., 2000) examined data from tasks that measure executive functioning and developed their three-factor model. In Miyake's model inhibition, updating and set-shifting all correlate highly with each other. This explains some of the variance in individual differences when making a decision. All three of the functions included in Miyake's model are crucial aspects of the dual-process framework: inhibition when overriding Type 1 processing; updating when differing working memory capacity is needed and set-shifting when changing from Type 1 to Type 2 processing (Del Missier et al., 2010; Del Missier, Mäntylä, & Bruin, 2012). The following sections will introduce some executive functions in more detail.

3.2.1 Inhibition

In the dual-process framework of judgement and decision-making, inhibition is an important executive function in the interaction between intuitive, Type 1 processing and analytic Type 2 processing (Schneider & Shiffrin, 1977; Evans, 2008). Since the dual-processes act in parallel (in the parallel models) with the fastest processes producing a solution, these models are the exception in not utilising an inhibition component (Epstein, 1973; Sloman, 1996). In the sequential and hybrid models incorrect Type 1 thinking must be inhibited in order to start correct Type 2 analytic thinking (Stanovich, 2009; Handley & Trippas, 2015). Inhibition starts when a conflict is detected between the two processes of decision-making (De Neys, 2014; Pennycook, Fugelsang, et al., 2015). For example, when considering the aforementioned engineer versus lawyer incongruent base-rate vignette, Type 1 (the engineer) and Type 2 (the lawyer) processes produce competing solutions. Upon noticing the conflict between the two solutions Type 2 processing overrides Type 1 processing, thereby correctly answering the problem with the 'lawyer' solution (Evans, 2006; 2008). A Type 1 solution is given when no Type 2 solution is available due to lack of knowledge or cognitive ability (Stanovich & West, 1997; Stanovich, 2009).

The neuromodulation research on inhibition focuses on the inhibition of prepotent automatic processes (Horvath et al., 2015a; Loftus et al., 2015). The Stroop task (Stroop, 1935) and stop-signal task (Horvath et al., 2015a) are both tasks that measure this type of inhibition and have been administered in tDCS studies (Duell et al., 2018). The effects of tDCS neuromodulation on inhibition is mixed – some studies find that tDCS boosts inhibitory control (Loftus et al., 2015) whilst other studies find that it does not (Duell et al., 2018).

3.2.2 Updating

Judgement and decision-making rely on information updating and monitoring in working memory, otherwise called updating (Miyake & Friedman, 2012; Miyake et al., 2000). Intuitive, Type 1 processing requires very little working memory capacity (WMC) as intuitive thinking is not affected by constraints imposed on WMC by the environment (Evans, 2012).

The capacity to update one's working memory should not influence Type 1 processing as it is deemed to proceed automatically without any interference from executive functions. Thus, for example, if two people (without Type 2 processing) were asked to answer the engineer versus lawyer incongruent base-rate vignette they would both likely arrive at the same Type 1 'engineer' solution even if one of these individuals was distracted. On the other hand, analytic Type 2 processing is severally limited by WMC (Hinson, Jameson, & Whitney, 2003; Evans, 2008). Type 2 processing requires high levels of WMC to function because analytic thinking requires the use of abstract thought that often includes cognitive simulation (i.e., thinking about consequences of a scenario) (Stanovich, 2009). When an individual has low WMC available they are less likely to engage in Type 2 processing (Evans, 2008; Stupple, Gale, & Richmond, 2013).

The neuromodulation research on updating is extensive with many studies measuring updating with the n-back and Sternberg tasks (Hill et al., 2016; Arciniega, Gözenman, Jones, Stephens, & Berryhill, 2018). The tDCS effects on updating is mixed with some studies finding an increase in updating after stimulation (Hill et al., 2016) and other studies finding no effect of neuromodulation (Imburgio & Orr, 2018).

3.2.3 Set-shifting

The final executive function that is crucial to the dual-process framework is mental set-shifting, also called task-switching, task-shifting, attention-switching and cognitive flexibility (Miyake et al., 2000; Monsell, 2003). One widely used example of set-shifting can be seen in the Stroop task (Sternberg, 1969). When one performs the Stroop task one must switch between different sets of instructions, for example, 'Name the colour of the word' or 'Read the word.' Set-shifting is important to the dual-process framework when switching between rules or instructions in Type 2 processing (Stanovich, 2009; Kiesel et al., 2010).

The neuromodulation studies that examine set-shifting primarily capture set-shifting by using task switching paradigms (Leite, Carvalho, Fregni, Boggio, & Gonçalves, 2013; Savic, Müri, & Meier, 2016). In these tasks, participants must switch between two instructions, for example 'Name the letter' or 'Name the number.' The effects of tDCS neuromodulation on set-shifting are mixed with reduced set-shifting after stimulation in one experiment (Leite et al., 2013) and no effect of stimulation in another study (Savic et al., 2016). Testing set-shifting is outside of the scope of this PhD thesis as there are no adequate tasks for examining this executive function.

3.3 Alternative perspectives on decision-making

Opponents of the dual-process framework of decision-making suggest that all judgement and decision-making can be mapped onto a single type of reasoning. Two of the single-type decision-making frameworks are bounded rationality (Simon, 1957) and dynamic graded continuum theory (Cleeremans & Jiménez, 2002).

3.3.1 Bounded rationality (Simon, 1957; 1991)

Bounded rationality does not posit that there are two types of decision-making (Type 1 and Type 2). It is the idea that individuals are limited (or bounded) in the ability to make decisions by time, cognitive ability, and cognitive capacity. Reasoners act as satisficers (meaning to satisfy and suffice) and choose the most satisfying response to a problem, rather than the optimum choice (Simon, 1991). This theory suggests that decision-making is a rational process for finding the optimal solution given the information provided. For example, when asked *"Which city has the largest population? (a) Hamburg or (b) Cologne"* reasoners often respond with the first city that comes-to-mind because they are acting upon the limited amount of information that they have available (Gigerenzer & Goldstein, 1996).

Scholars of the dual-process framework respond to bounded rationality in three ways. Firstly, judgement and decision-making research that use reaction time data find that errorful Type 1 processing is always quicker than analytic Type 2 processing (Handley & Trippas, 2015; Pennycook, Fugelsang, et al., 2015). Secondly, evidence exists that clearly show that an ancient, intuitive form of decision-making evolved in our ancestors whilst analytic thinking evolved with language. Non-human primates, of which we share common ancestors have the capacity to make decisions that are consistent Type 1 processing but not analytic Type 2 decisions (Chen, Lakshminarayanan, & Santos, 2006; Krupenye, Rosati, & Hare, 2015). The third major piece of evidence for dual-process framework is that Type 1 and Type 2 processing have different neural substrates (Hare et al., 2009; Greenwood, Blumberg, & Scheldrup, 2018). Intuitive, affective, Type 1 processing is linked to the left DLPFC (Hare et al., 2009; Oldrati, Patricelli, Colombo, & Antonietti, 2016) whilst analytic Type 2 processing is associated with impulsivity control and set-shifting in the right DLPFC (Loftus et al., 2015; Tayeb & Lavidor, 2016).

3.3.2 Dynamic graded continuum theory (Cleeremans & Jimenez, 2002)

Dynamic graded continuum theory is a learning framework that posits that the quality (i.e., it’s strength, distinctiveness and stability) of a representation or simulation can be mapped onto a continuum with intuitive, implicit (Type 1) processes and analytic, explicit (Type 2) reasoning at opposite ends of the continuum (Osman, 2004; Barrouillet, 2011). Implicit or explicit information leads to the corresponding type of learning and decision-making. When an individual makes a decision about some information and it is processed quickly, under time constraints then the solution is consistent with Type 1 processing. If given sufficient time to construct a solution to the information then the solution is consistent with analytic, Type 2 processing. The crucial aspect of this theory is that unlike the dual-process framework all solutions can be plotted on this continuum based on the quality of the solution.

3.4 Individual differences and dual-process theory

Individual differences in thinking disposition (West, Toplak, & Stanovich, 2008; Shenhav, Rand, & Greene, 2012), cognitive ability (Frederick, 2005; West et al., 2008) and cognitive capacity / working memory capacity (Hinson et al., 2003; Gómez-Chacón, García-Madruga, Vila, Elosúa, & Rodríguez, 2014) all influence decision-making. Thinking dispositions that include a tendency towards religiosity (Pennycook, 2014), open-mindedness (Stanovich & West, 1997) and need for cognition (Cacioppo & Petty, 1982) influence an individual's use of intuitive (Type 1) and analytic (Type 2) reasoning. Individuals with high cognitive ability (intelligence) make more analytic decisions, whilst avoiding errorful intuitive responses (Stanovich & West, 2008). Whilst cognitive capacity moderates analytic thinking (Type 2), reasoners with high working memory capacity make more analytic decisions (Evans & Stanovich, 2013) whilst individuals with low working memory capacity are restricted to making intuitive decisions (De Neys, Schaeken, & d'Ydewalle, 2005).

Some of the models of dual-process reasoning such as Stanovich's (2009) tripartite model and Evans' (2006) revised heuristic-analytic model account for the variability in individual differences. Stanovich's tripartite model posits that an individual's belief system (thinking disposition) is located in his reflective mind whilst their fluid intelligence if located in the algorithmic mind where these can influence the outcome of reasoning. Evans' revised heuristic-analytic model places cognitive ability (*general intelligence*) in his analytic system intervention function where it can influence reasoning. However, some models such as Evans' (1989) heuristic-analytic model and

De Neys' (2012) logical intuition model do not include functions by which individual differences can mediate decision-making.

3.5 Critiques of dual-process theory

3.5.1 Why is there no singular or agreed version of dual-process theory?

Critics of dual-process theory suggest that the lack of a consensus about a single version of dual-process theory is a weakness (Keren & Schul, 2009; Kruglanski & Gigerenzer, 2011). The diverse range of dual-process theories have their roots in domains ranging from memory (Pellegrino, Rosinski, Chiesi, & Siegel, 1977; Smith & DeCoster, 2000), learning (Sun, Slusarz, & Terry, 2005; Chandrasekaran, Yi, & Maddox, 2014) and social psychology (Chaiken, 1980; Rydell & McConnell, 2006). It is important to note that whilst all of these domains of research have dual-process theories that use similar terminology (e.g., implicit / explicit processing) these processes are not the identical; these terms are simply used differently (Evans, 2012). In general, the social psychology dual-process theories are concerned with consciousness and moral responsibility, rather than cognitive architecture (Evans, 2008).

In the reasoning, judgement and decision-making literature the lack of a unified dual-process theory reflect the notion that not all dual-process theories refer to the same underlying processes (Evans & Stanovich, 2013). For example, in Type 2 processing Stanovich emphasises the decoupling operation whilst Evans maintains the importance of a central working memory resources (Evans & Stanovich, 2013). In this thesis Type 2 processing is defined as relying on a decoupling operation and a central working memory resource.

3.5.2 Are heuristics and biases unique to Type 1 processing?

Some critics of dual-process theory (Kruglanski & Gigerenzer, 2011) propose that heuristics and biases (i.e., systematic patterns of deviation from the norm) are not unique to Type 1 processing (Evans, 2012). They state that errorful responses, which are a result of heuristics and biases can arise when processing information through Type 1 thinking or Type 2 thinking (Evans, 2006; Stanovich, 2009). These dual-process theorists respond to this by explaining that Type 1 thinking does have the capacity to produce the correct answer to a problem some of the time, however, this is only possible if the correct answer is consistent with Type 1 processing (i.e., see congruent base-rate vignettes in Chapter 7) (Evans, 2006). The problem with rapid decision-making is that it is very susceptible to errorful and biased responses (Amos Tversky & Kahneman, 1973; Croskerry, 2009).

The dual-process theorist Evans explains in his "revised heuristic-analytic model" that heuristics and biases are attributes of Type 1 processing (Evans, 2006). In his model he says that errorful biased decision-making can arise through Type 2 processing when the explicit representation of information is manipulated incorrectly through working memory which appears as if these heuristics and biases were used in Type 1 processing when they were not (Evans, 2006; 2012).

3.5.3 Is fast processing always indicative of Type 1 rather than Type 2 use?

Critics of dual-process theory question whether a rapid response to information is necessarily indicative of Type 1 processing (Evans, 2012). When heuristics and biases are used effortlessly, unconsciously and during uncertainty the information is processed rapidly which is indicative of Type 1 use (Evans, 2008). When Type 2 processing is used this is slower than the former because to make an analytic decision cognitive resources such as working memory need to be dedicated to the careful processing of information (Evans, 2012). Reaction time analysis is beyond the scope of this PhD thesis as the focus is on accuracy using either Type 1 or Type 2 processing.

3.5.4 Why is Type 1 processing domain-specific whilst Type 2 is abstract?

Some dual-process theorists and critics of dual-process theory highlight the descriptions of some of the aspects of Type 1 processing as contextualised, domain-specific (e.g., in finance of medical decision-making) and concrete, and Type 2 processing as abstract, rule-based and decontextualized (Evans & Stanovich, 2013).

Evans suggests that this is not correct (Evans & Stanovich, 2013): if Type 1 processing is always domain-specific then many of the heuristics and resulting biases would only work within specific domains of decision-making. For example, if this were correct then the framing bias, that states that our decisions are influenced by the way in which information is presented (i.e., ‘framed), would not work across multiple domains of decision-making. Contrary to this, we have clear evidence that the framing bias influences decision-making in many domains including policy making and pension investments (Van Rooij, Kool, & Prast, 2007; Morton, Rabinovich, Marshall, & Bretschneider, 2011).

If Type 2 processing is as abstract as these critiques suggest then the other attributes of Type 2 thinking such as slow, rule-based, and explicit characteristics would be limited to abstract reasoning, for example when solving mathematics problems – this is not the case as Type 2 processing can also be applied to problems that are not abstract (Evans, 1984; Verschueren, Schaeken, & d’Ydewalle, 2005).

3.5.5 What is the evidence for the old (Type 1) and new (Type 2) processes?

Critics of dual-process theory question the idea of Type 1 processing as evolutionary ancient whilst Type 2 processing is evolutionary young, and uniquely human (Evans, 2006). They say that there is little evidence to support idea about the ancient origin of Type 1 processing and modern Type 2 processing (Evans, 2012).

Supporters of the evolutionary ancient Type 1 idea have two sources of evidence to support this view: (i) the recent observation of heuristics in non-human animals (i.e., other primates), and (ii) the association of Type 2 processing with language and associative learning in humans. Evolutionary psychologists and zoologists have observed the framing bias in chimpanzees (*Pan trogladytes*) (Krupenye et al., 2015) and capuchin monkeys (*Cebus appela*) (Chen et al., 2006), and the sunk cost bias in pigeons (*Columba livia*) (White & Magalhães, 2015). According to molecular-clock estimates the hominid genus split from our common ancestor with the non-human primates about 23 million years ago which supports the idea that some of the components of Type 1 thinking must have evolved during this early part of our evolution (Campbell, 2012). Since no evidence of Type 2 processing have been observed in other animals (other than human) theorists posit analytic thinking is evolutionary young and therefore evolved when humans developed the capacity to use higher cognition and language (Evans, 2006; 2008). One caveat here is that the description of Type 1 thinking as evolutionary ancient may be oversimplified as the different forms of implicit processing evolved at different times (Evans, 2006).

3.5.6 Are decision-making processes on a continuum, rather than discrete types?

Some critics of dual-process theory suggest that there are no distinct types of processing that underpin decision-making (e.g., intuitive and analytic) (Cleeremans & Jiménez, 2002). Rather than unique types of processes opponents of dual-process theory state that all decision-making processes can be mapped onto a continuum of processing style (Cleeremans & Jiménez, 2002). Evans and Stanovich maintain that the notion of a continuum of processing style arise from the confusion between *modes* and *types* of decision-making processing (Evans & Stanovich, 2013). Modes of processing are forms of Type 2 thinking that differ in individual differences for thinking dispositions. For example, when Type 2 processing is defined as the explicit processing of rules through the allocation of working memory resources modes of processing are engaged to explain the variance in decision-making (i.e., slow and reflective, or fast and intuitive). These modes of processing are measured with scales such as the Actively Open-Minded Thinking scale (AOT - Stanovich & West, 1997), Rational Experiential Inventory (REI - Pacini & Epstein, 1999), and Need for Cognition (NFC - Cacioppo & Petty, 1982) measure thinking disposition. In this thesis decision-making is mapped onto the dual-processing framework, with thinking dispositions (i.e., modes) accounting for some of the variability in decision-making outcome.

3.5.7 'The cluster problem': why aren't the attributes of Type 1 and 2 processes reliably aligned?

Critics of dual-process theory suggest that the attributes (i.e., binary characteristics) of the dual-process framework are not reliably aligned between models (Keren & Schul, 2009). According to the opponents of dual-process theory these attributes (e.g., affective-cognitive, automatic-controlled) are clustered together by selecting the relevant attributes and discarding everything else that does not fit with this attribute (Keren & Schul, 2009). Furthermore, they maintain that the attributes of the two cognitive processes (Type 1 and Type 2) are not always observed together.

Dual-process theorists concede that the attributes are not always reliably aligned (Evans & Stanovich, 2013). However, although the critics of dual-process theory maintain that this is a problem for the dual-processing account of decision-making, (Kruglanski & Gigerenzer, 2011), it is not (Evans & Stanovich, 2013). Evans replies to this critique by stating that the 'cluster problem' is only a problem if all attributes are considered to be necessary defining features of the Type 1 and Type 2 processing (Evans & Stanovich, 2013).

3.6 Decision-making: Dual parallel, sequential, hybrid - or a single process?

The question of whether analytic and intuitive decision-making are constituent parts of a dual-process model that work in parallel (Pacini & Epstein, 1999) or sequentially (Pennycook, Fugelsang, et al., 2015), or as antipodes of a single process (Barrouillet, 2011) varies among scholars. Sequential model dual-process theorists emphasise the importance of reaction time when making a decision were analytic (Type 2) decisions start after the earlier intuitive (Type 1) process: Type 1 response latencies are always shorter than Type 2 response latencies (De Neys, 2012). The parallel model dual-process theorists posit that both decision processes start at the same time, the first process to produce a response resolves the problem (Sloman, 1996). The hybrid model dual-process theorist incorporate feedback loops into their models emphasising accuracy over reaction time (Evans, 2006). The type of data used (i.e., accuracy or reaction time) is therefore one of the crucial factors in deciding which model to map experimental data to.

In this thesis accuracy data is recorded for analysis in each of the experiments. Judgement and decision-making, and executive functioning data is collected, mapped onto dual-process theories and assessed. In particular, individual differences in thinking dispositions are recorded and used as covariates to examine whether performance on these measures modulate Type 1 or Type 2 thinking. When paired with the neuromodulatory manipulations the neural substrates of the dual-process framework is examined through the use of Stanovich's tripartite model of decision-making.

Chapter 4

A systematic review and meta-analysis of the effects of tDCS neuromodulation on decision-making in the dual-process framework

4.1 Introduction

The dual-process framework suggests that there are qualitative differences in cognitive processes (or related neural systems) in decision-making. Type 1 processes are associated with intuitive decisions based on rapid associations requiring low effort, and Type 2 processes are based on slow reflective consideration of the decision problem (Evans, 2008). The former is often associated with mental short-cuts, hereafter referred to as heuristics, which are presumably employed when cognitive resources are scarce, and often lead to judgement or decision bias, that is, suboptimal (or wrong) answers according to a normative standard (Tversky, Kahneman, Wendt, & Vlek, 1975). Type 2 processes are associated with normative correct responses in judgement and decision tasks. Furthermore, risky decision-making refers to decision-making under uncertainty about the outcome of a decision (Lejuez et al., 2002). High levels of risky decision-making are associated with low levels of inhibition, which is in turn linked with Type 1 decision-making processes, whilst high inhibitory control over pre-potent responses is often associated with Type 2 decision-making (Evans, 2008).

TDCS has been applied in a number of decision-making studies, such as affective and deliberate risk-taking (Ly et al., 2016), use of heuristics in judgement and decision-making (Votinov, Aso, Koganemaru, Fukuyama, & Mima, 2013) as well moral judgement (Sellaro, Derks, et al., 2015). The effects of tDCS on decision-making have included improved accuracy, for example in the affective bias task (Ly et al., 2016), but also reduced accuracy, such as in the probabilistic guessing task (Hecht, Walsh, & Lavidor, 2010). In risk decision-making tasks, namely the Balloon Analogue Risk Task (BART), tDCS was found to reduce risk-taking behaviour when participants are asked to make decisions about continuing to increase the size of a balloon which increases the risk of the balloon bursting and thus losing their credit or whether to bank some of their accumulated credit with the increasing size of the balloon and potentially lose out on gaining additional credit (Cheng & Lee, 2015).

It is proposed that a potential explanation for the disparate effects of tDCS on decision-making is whether the task was linked to Type 1 processes which are associated with increased decision bias, Type 2 decision-making which are linked with decreased decision bias, or to risky decision-making. Here the effects of tDCS on decision-making were examined in a systematic review and meta-analysis.

Whilst there has not yet been a meta-analysis of the effects of tDCS in decision-making, Hill, Fitzgerald and Hoy (2015) performed a meta-analysis of the effects of tDCS on working memory. In the dual framework model, working memory is linked with Type 2 processes. Hill et al., (2015) found a small albeit statistically significant reduction in reaction time and a trend towards an improvement in accuracy following offline anodal tDCS, which was applied before the working memory tasks. In contrast, the effects on reaction time and accuracy did not reach significance during online stimulation, which was applied during the task (Hill et al., 2015). In these studies, tDCS had been applied to the dorsolateral prefrontal cortex (14 studies) as well as to orbitofrontal region (4 studies). When tDCS is applied specifically to the dorsolateral prefrontal cortex, Dedoncker et al.'s (Dedoncker, Brunoni, Baeken, & Vanderhasselt, 2016) meta-analysis found an improvement in reaction time during cognitive tasks with a single session of anodal tDCS in healthy participants, but there were no changes in accuracy. This effect was evident whether the stimulation was online or offline and whether applied to either the right or left dorsolateral prefrontal cortex.

The studies were grouped by assessing the site of the anodal stimulation (left versus central and right locations) and whether stimulation increased bias (Type 1 or Type 2). As anodal tDCS applied to the dorsolateral prefrontal cortex has been found to improve accuracy in cognitive tasks, which included working memory, and working memory is associated with Type 2 decision-making (Stanovich, 2009), anodal tDCS when applied to the dorsolateral prefrontal cortex would be expected to improve outcome in Type 2 decision-making tasks. It was hypothesized that anodal tDCS applied to the left dorsolateral prefrontal cortex would improve Type 2 decision-making processes and that susceptibility to Type 1 processes would be reduced.

4.2 Research questions

In this Chapter, the influence of tDCS over the right and / or left dorsolateral prefrontal cortices (DLPFC) on tasks that tap the dual-process framework of decision-making were examined for both intuitive thinking (Type 1) and cognitive reflection (Type 2).

Research question 1

Does online anodal tDCS of either the right DLPFC or left DLPFC alter the propensity to use Type 2 decision-making over Type 1 decision-making compared to sham?

Prediction 1: anodal stimulation of the right and left DLPFCs will increase the propensity to use Type 2 decision-making during stimulation as shown by higher scores that are consistent with Type 2 responses compared to Type 1 responses.

Research question 2

Does offline anodal tDCS of either the right DLPFC or left DLPFC alter the propensity to use Type 2 decision-making over Type 1 decision-making compared to sham?

Prediction 2: anodal stimulation of the right and left DLPFCs will increase the propensity to use Type 2 decision-making after stimulation as shown by higher scores that are consistent with Type 2 responses compared to Type 1 responses.

Research question 3

Does online anodal tDCS of the right DLPFC or left DLPFC alter risk-taking behaviour compared to sham?

Prediction 3: anodal stimulation of the right DLPFC will decrease risk-taking behaviour during stimulation as shown by lower risk-taking scores in the BART during stimulation compared to sham.

Research question 4

Does offline anodal tDCS of the right DLPFC or left DLPFC alter risk-taking behaviour compared to sham?

Prediction 4: anodal stimulation of the right DLPFC will decrease risk-taking behaviour after stimulation as shown by lower risk-taking scores in the BART during stimulation compared to sham.

4.3 Methodology

A search of the literature and the meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) guidelines (Moher, Liberati, Tetzlaff, & Altman, 2010).

4.4 Literature review

The literature search was conducted using Scopus, Medline (PubMed), PsychINFO (Ovid) and Science Direct electronic databases with the criteria: “decision-making” or "heuristic" or "judgment" or "judgement" and either “tDCS” or “transcranial direct current stimulation” or “direct current stimulation” or “transcranial alternating current stimulation” or “TACS” or “transcranial random noise stimulation” or “tRNS” or “neuromodulation” in all fields in Science Direct and Wiley Online, and limited to articles title, abstract and keywords in Scopus, with publication dates ranging from 1966 to December 2016 (see Figure 4.1).

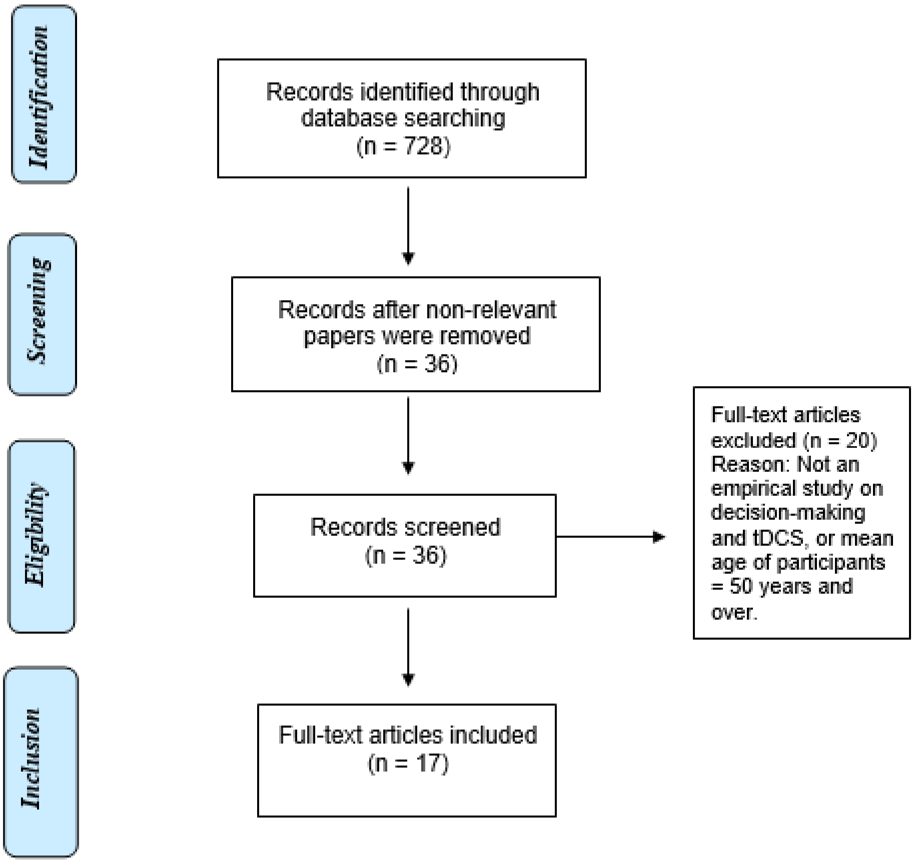


Figure 4.1. Flow chart for the database search using the Preferred Reporting for Systematic Reviews and Meta-Analyses (PRISMA).

4.5 Selection criteria

Inclusion criteria were: (1) tDCS; (2) healthy participants; (3) adult ages18-65 years; and (4) articles written in English. The exclusion criteria were non-human studies, theoretical articles and commentaries without any statistical analysis and case reports.

The studies were assessed according to the type of the targeted decision-making process, Type 1 (increase of decision bias) and Type 2 (decrease of decision bias) processing.

4.6 Data extraction

The following demographics were extracted: sample size, gender, age, years of education, and handedness. The following parameters of the experimental designs were coded: tDCS montage locations (e.g., right DLPFC, left DLPFC), electrode size (cm^2), type of electrode (anodal / cathodal or reference), session duration (seconds), within or between-group design, current intensity (mA), current density (mA/cm^2), fade-in (duration of the gradual onset and increase in current intensity), fade-out (duration of the gradual decrease and end in current intensity) and whether tDCS was used in an online or offline paradigm (Table 4.1). Behavioural task measures (accuracy and reaction time) were extracted for active, sham (i.e., same protocol as active, but with tDCS turned off) and control groups (i.e., no tDCS) for analysis.

Data from novel tasks included Ye, Chen, Huang, Wang, Jia, et al.,'s (2015) risk-aversion task, Sellaro, Güroğlu, et al.,'s (2015) Moral Judgement Task (MJT), Minati, Campanhã, Critchley, and Boggio's (2012) Gambling Task, Hecht et al.,'s (2010) Probabilistic Guessing Task, Colombo, Balzarotti, and Mazzucchelli's (2016) object valuation task, and Ly et al.,'s (2016) Affective Biasing and Instrumental Action Task.

4.7 Search results

4.7.1 Study selection

A total of seventeen papers met the inclusion and exclusion criteria consisting of forty-three independent participant samples in eighteen studies. One paper met a criteria for exclusion with a mean age of participants in the experimental group of sixty-nine years or above (Boggio et al., 2010) which was considerably more than any of the other studies included in this review.

The majority of the studies utilized risk decision-making tasks such as the BART (5 studies, 126 participants) (Cheng & Lee, 2015; Fecteau et al., 2007 -2 studies; Gorini, Lucchiari, Russell-Edu & Pravettoni, 2014; Ouellet et al., 2015) and Columbia Card Task (CCT; 1 study, 29 participants (Pripfl, Neumann, Kohler & Lamm, 2013)). In the Type 1 tasks, heuristic-based strategies can be used to complete the task: endowment effect task (1 study, 12 participants (Votinov, Aso, Koganemaru, Fukuyama & Mima, 2013)), Moral Judgement Task (MJT, 1 study, 60 participants (Sellaro et al., 2015)), Implicit Association Task (IAT, 1 study, 60 participants (Sellaro et al., 2015)), affective biasing and instrumental action task (1 study, 120 participants (Ly et al., 2016)), and the Cognitive Reflection Test when scored as incorrect answers (1 study, 39 participants) (Oldrati, Patricelli, Colombo & Antonietti, 2016). Type 2 tasks included the temporal discounting task (1 study, 14 participants (Hecht et al. 2013)), probabilistic guessing task (1 study, 28 participants (Hecht et al., 2010)), paired lottery choice task (PLCT; 2 studies, 120 participants (Ye et al., 2015a; 2015b), choice induced preference change task (CIPT, 1 study, 48 participants (Mengarelli, Spoglianti, Avenanti & Di Pellegrino, 2015)), and Cognitive Reflection Test when scored as correct answers (1 study, 39 participants) (Oldrati et al. 2016).

Behavioural testing for all offline stimulation studies started immediately after the stimulation ended (Ye et al., 2015a: 2015b; Gorini et al., 2014; Ouellet et al., 2015). The statistical heterogeneity of I^2 was high for all of the datasets included in this analysis (93% to 97%), which is to be expected because of the variety of tasks.

4.7.2 Demographic data

A total of 710 healthy participants were included in the present analysis (351 females, 195 males, and 164 sex not stated; age range 18 - 36 years: mean age ± SD, 24.71 ± 3.01 years) (see Table 4.1). For one study that had a clinical sample, the healthy participants were selected only (Gorini, Lucchiari, Russell-Edu, & Pravettoni, 2014).

Table 4.1 summarizes the studies included in the meta-analysis. Because of the heterogeneity of tasks, predictions, montages, and stimulation sites, the studies were grouped along 2 main criteria: (i) tasks: risk-taking versus decision-making-tasks; and (ii) stimulation site (left versus other).

Table 4.1. Parameters and demographics of studies included in the meta-analysis.

First author	Date	N	Age (SD) years	Sex (Female / Male)	Intensity (mA)	Task	Online / Offline	tDCS montage (anode / return)	Current duration (minutes)
Type 1									
Votinov	2013	12	23.3 (1.7)	3/9	2	EET	Online	(i) F6-Fp1, (ii) Fp1-F6	20
Sellaro	2015	60	21.9 (np)	39/21	1	IAT	Offline	(i) Fpz-Oz, (ii) Oz-Fpz, (iii) sham	20
Sellaro	2015	60	22.1 (2.3)	14/6	1	MJT	Offline	(i) Cp6-Fp1, (ii) Fp1-CP6, (iii) sham	20
Ly	2016	121	21.8 (2.6)	Np	1	Affective bias task	Online	(i) Fp1, Fp2-inion, (ii) Inion-Fp1, Fp2, (iii) sham	25
Oldrati (incorrect)	2016	39	25.3 (8.04)	24/15	1.5	CRT	Offline	(i) F3-mastoid, (ii) mastoid-F3, (iii) sham	20
Type 2									
Hecht	2010	28	22.8 (2.4)	14/14	2	PGT	Online	(i) F3-F4, (ii) F4-F3, (iii) sham	22
Minati	2012	47	21.6 (1.5)	47/0	2	GT	Online	(i) F3-F4, (ii) F4-F3, (iii) sham	20.5
Hecht	2013	14	26.7(3.3)	7/7	1.6	TDT	Online	(i) F3-F4, (ii) F4-F3, (iii) sham	20
Mengarelli	2015	48	24.7 (9.4)	28/20	1	CIPCT	Offline	(i) Fp1-F3, (ii) Fp2-F4, (iii) sham	15
Ye	2015	60	21.4 (np)	35/25	2	PLCT	Offline	(i) F3-F4, (ii) F4-F3, (iii) sham	15
Ye	2015	60	21.3 (np)	36/24	2	PLCT	Offline	(i) F3-F4, (ii) F4-F3, (iii) sham	15
Colombo	2016	30	24.5 (2.7)	20/10	1.5	AFT	Offline	(i) F3-mastoid, (ii) mastoid-F3, (iii) sham	20
Oldrati (correct)	2016	39	25.3 (8.04)	24/15	1.5	CRT	Offline	(i) F3-mastoid, (ii) mastoid-F3, (iii) sham	20
Risk									
Fecteau (Study 1)	2007	35	21 (3.9)	26/9	2	BART	Online	(i) F3-F4, (ii) F4-F3, (iii) sham	20
Fecteau (Study 2)	2007	12	21.7 (3.6)	11/1	2	BART	Online	(i) F4-Fpz (ii) F3-Fpz	20
Pripfl	2013	18	22.4 (1.7)	10/8	1	modified CCT	Online	(i) F1, F3, AF1-F4, (ii) F2, F4, AF2-F3	15
Gorini	2014	18	36.8 (7.8)	8/10	1.5	BART, GDT	Offline	(i) F3-F4, (ii) F4-F3, (iii) sham	18
Cheng	2015	16	20.9 (1.9)	NP	2	BART	Online	(i) F3-F4, (ii) F4-F3, (iii) sham	<19
Ouellet	2015	45	25.1 (4.9)	29/16	1.5	BART, IGT	Offline	(i) Fp1-Fp2, (ii) Fp2-Fp1, (iii) sham	30

Number of participants is presented with the number of female participants in parenthesis. Mean age is presented in years with standard deviation (SD) in parenthesis. Abbreviations: NP = Not Presented, N/A = not applicable, BART = Balloon Analogue Risk Task, RT = Risk Tasking, GDT = Game of Dice Task, IGT = Iowa Gambling Task, PLCT = Paired Lottery Choice Task, GT = novel Gambling Task, CCT = Columbia Card Task, Endowment Effect Task , IAT = Implicit Association Task, PGT = Probabilistic Guessing Task, TDT = Temporal Discounting Task, CIPCT = Choice Induced Preference Change Task, CRT = Cognitive Reflection Test, MJT = Moral Judgment Task and AFT = Affect-Functional Task. For the Oldrati paper incorrect CRT answers were included in under Type 1, whilst correct CRT answers were included in Type 2 - all participants took part in three, independent sessions completing all three conditions (i, ii and iii). Significant results are indicated with an asterisk (*).

4.7.3 Decision-making tasks

Endowment Effect Task: This task measures the degree to which an individual believes that an item is of greater value than another identical item simply because the individual possesses it (Morewedge & Giblin, 2015). The effect is evident in the willingness to pay or to accept in payment for an object which the participant owns (Votinov et al., 2013). The data used in this review from this study refer to a willingness to accept / willingness to pay ratio, and a high ratio indicates high bias.

Implicit Association Task: A measure of associations which are implicitly held, providing a measure of implicit bias (Sellaro, Derks, et al., 2015). Participants are presented with two lists of names, one list of familiar names from the same ethnicity (in-group) and a list of unfamiliar names from a different ethnicity (out-group) with an affective attribute (e.g., joy or sadness). They are then given a short moral scenario with a name from one of the lists and rate the permissibility of the actions. The data used from the study (Sellaro, Derks, et al., 2015) refer to a compound score that represents the difference between congruent and incongruent blocks scores, a high compound score is indicative of high implicit bias.

Probabilistic Guessing Task: In this task, people use the matching bias, a heuristic which tries to maximize payoffs from independent chance events based on historic distributions (Kallir & Sonsino, 2009), which has been measured in the probabilistic guessing task (Hecht et al., 2010). Participants watch an asterisk that appears either above or below a central fixation point and must guess the location of the next asterisk. The location of the asterisk is presented with a greater likelihood in one of the two locations. The data used from the study in this review (Hecht et al., 2010) refer to the mean prediction accuracy in block 1 (immediately after tDCS ended) of the task.

Affective Biasing and Instrumental Action Task: The task examines the effect of affective biasing on instrumental decision-making (Ly et al., 2016). The task contains two separate stages: a learning phase and a transfer phase. In the learning phase, a probabilistic learning task is used to learn an instrumental response. In the transfer phase, the probabilistic learning task is used with the addition of affective (happy or angry) faces that precede the instrumental target. The data used from the study (Ly et al., 2016) refer to the mean proportion of go responses for the approach angry transfer phase.

Paired Lottery Choice Task: A form of gambling task which measures risky decision-making (Ye, Chen, Huang, Wang, Jia, et al., 2015; Ye, Chen, Huang, Wang, & Luo, 2015). Participants decide between a safe option with no risk (i.e., neither win nor lose money) or an option with a risk (e.g., 60% chance of losing £5 and 60% of gaining £20). The aim of the task is to maximize the total monetary score at the end of the round. The data used from the study in the present review (Ye, Chen, Huang, Wang, Jia, et al., 2015; Ye, Chen, Huang, Wang, & Luo, 2015) refer to the mean weighted risk aversion measure.

Temporal Discounting Task: A measure of the propensity to delay a greater monetary reward or accept a smaller reward immediately (Bickel & Marsch, 2001; Hecht, Walsh, & Lavidor, 2013). The propensity to delay or accept the reward with the monetary value of the reward is used as the measure of temporal decision-making. The data used from this study (Bickel & Marsch, 2001; Hecht et al., 2013) refer to the mean percentage of immediate choice made within the first minutes of the task.

Cognitive Reflection Test (CRT): A behavioural measure of automatic-heuristic Type 1 and controlled-reflective Type 2 decision making processing (Frederick, 2005; Oldrati et al., 2016). Participants view short questions (e.g., *A bat and ball together cost £1.10, The bat costs £1 more than the ball. How much does the ball cost?*) that are designed to initially elicit an incorrect intuitive (Type 1) answer (e.g., *10 pence*). After viewing the question and being given enough time to think about their reply, participants arrive at the correct (Type 2) answer (e.g., *5 pence*). Crucially, there is a third potential answer that is also incorrect (e.g., *Anything other than 10 or 5 pence*) The data in this review refer to either the mean accuracy of correct answers in Type 2 analysis or the mean number of incorrect answers in Type 1 analysis.

Choice Induced Preference Change Task: A modified version of Brehm's free-choice task (Brehm, 1956) which measures implicit choice and implicit choice change to works of art was used. The task contains four stages that modulate the preference and memory for an item (e.g., piece of art) (Izuma & Murayama, 2013; Mengarelli, Spoglianti, Avenanti, & Di Pellegrino, 2015). The data from this study (Mengarelli et al., 2015) refer to the mean preference for selected art at phase 3 of the task.

Moral Judgement Task: Participants rate the moral permissibility of hypothetical scenarios (Sellaro, Güroğlu, et al., 2015). The data from this study (Sellaro, Güroğlu, et al., 2015) refer to the mean moral judgement on a 7-point Likert scale.

Balloon Analogue Risk Task (BART): Participants 'inflate' a series of balloons. As the balloon get bigger, the potential reward gets bigger. However, every trial will end with the balloon popping if the participant continues to press the button, resulting in a loss of earnings. The only sure way to retain earnings is to decide to stop pressing. Greater control results in a higher sum of rewards at the end of the task (Lejuez et al., 2002).

4.8. Meta-analyses

All studies included in this analysis used continuous outcome measures, and mean scores and standard deviations were used for the present analysis. Where standard deviations were missing, these were calculated from the reported standard errors (see Meron, Hedger, Garner, & Baldwin, 2015). In 7 studies (Cheng & Lee, 2015; Pripfl et al., 2013; Ouellet et al., 2015; and Hecht et al., 2010; Oldrati et al., 2016; & 2 studies in Fecteau et al., 2007), there were identical sham groups for otherwise independent experiments. To avoid a unit-of-analysis error due to the correlation between the effects from multiple comparisons, the sham groups were evenly split as per the recommendation in the Cochrane Handbook for Systematic Reviews and Interventions (Higgins & Green, 2005).

Due to the different decision-making task scores that were used in these studies the standard mean difference (SMD) of the mean total scores were used as an index of effect size because it allows for a direct comparison between studies with different scales (Deeks & Higgins, 2010). Review Manager Software package (version 5.3) was used to calculate effect sizes (Meron et al., 2015). Review Manager calculates Hedge's adjusted *g,* an effect size measure that is similar to Cohen's *d*, but includes an adjustment to account for small samples bias (Higgins & Green, 2005). The effect sizes can be interpreted by using the same convention as Cohen's *d*, namely small (≥ 0.2), medium (≥ 0.5) or large (≥ 0.8).

A number of studies had included both baseline and sham conditions. In these cases, the measures from the sham conditions were used as the means of comparison for these studies. For consistency, studies which contained both unilateral and bilateral conditions were compared using the same process in analysis.

4.8.1 Tests of heterogeneity

Statistical heterogeneity was assessed by utilizing the I^2 statistic (Hedges & Vevea, 1998). I^2 evaluates the appropriateness of pooling individual study results with a range between 0% and 100%: 0% indicates that there is no heterogeneity between studies while 100% suggests that there is a very high level of heterogeneity.

A random-effects model was chosen because it is more appropriate for analysing data from a variety of independent studies, and it is considered to be better at accounting for differences in effect sizes across studies than the fixed-effects model (Hedges & Vevea, 1998).

4.8.2 Results

4.8.2.1 TDCS effects on risk-based decision-making

Risk-taking behaviour was examined in a total of 6 studies in 5 articles that used the BART (Fecteau, Pascual-Leone, et al., 2007; Pripfl et al., 2013; Gorini et all., 2014; Cheng & Lee, 2015) and the Columbia Card task (Ouellet et al., 2015) – one article (Fecteau, Pascual-Leone et al., 2007) contained two studies that included the BART. Behavioural measures for the analysis were accuracy, as reaction times were not reported in all studies. Overall, comparison of the effect sizes in these studies showed that online tDCS significantly reduced risk-taking behaviour as measured by the BART and Columbia Card Task (SMD = -0.86, 95% CI = -1.53, -0.18, p = 0.01), which was attributable to online stimulation of left DLPFC, whilst offline tDCS (Gorini et al., 2014; Ouellet et al., 2015) did not show any significant effect (SMD = -0.02, 95% CI = -0.50, 0.44, p = 0.99) in comparison to sham (Figure 4.2).

Looking at the online stimulation only, anodal tDCS to the left DLPFC was associated with a significant reduction in risk-taking behaviour as measured by mean BART adjusted pumps and Columbia Card Task as compared to sham (SMD = -1.05, 95% CI = -2.11, 0.01, p = 0.05), based on 4 studies (Fecteau, Pascual-Leone, et al., 2007; Pripfl et al., 2013; Cheng & Lee, 2015) (Figure 4.2). However, stimulation of the right DLPFC did not reduce risk-taking behaviour (SMD = -0.70, 95% CI = -1.7, 0.30, p =

0.17) (Fecteau, Pascual-Leone, et al., 2007; Pripfl et al., 2013; Cheng & Lee, 2015) as compared to sham.

For the offline anodal stimulation only, there were 2 studies in which tDCS was applied to the orbitofrontal cortex (Ouellet et al., 2015) or DLPFC (Fecteau, Pascual-Leone, et al., 2007). Effect sizes revealed that tDCS to either the left orbitofrontal cortex (Ouellet et al., 2015) or DLPFC (Fecteau, Pascual-Leone, et al., 2007) or right prefrontal cortices (orbitofrontal cortex (Ouellet et al., 2015)) or DLPFC (Fecteau, Pascual-Leone, et al., 2007) did not significantly reduce risk-taking behaviour as measured by mean BART adjusted pumps in comparison to sham (SMD = -0.03, 95% CI = -0.70, 0.62, p = 0.90, and SMD = -0.02, 95% CI = -0.67, 0.63, p = 0.90, respectively) (Figure 4.2).

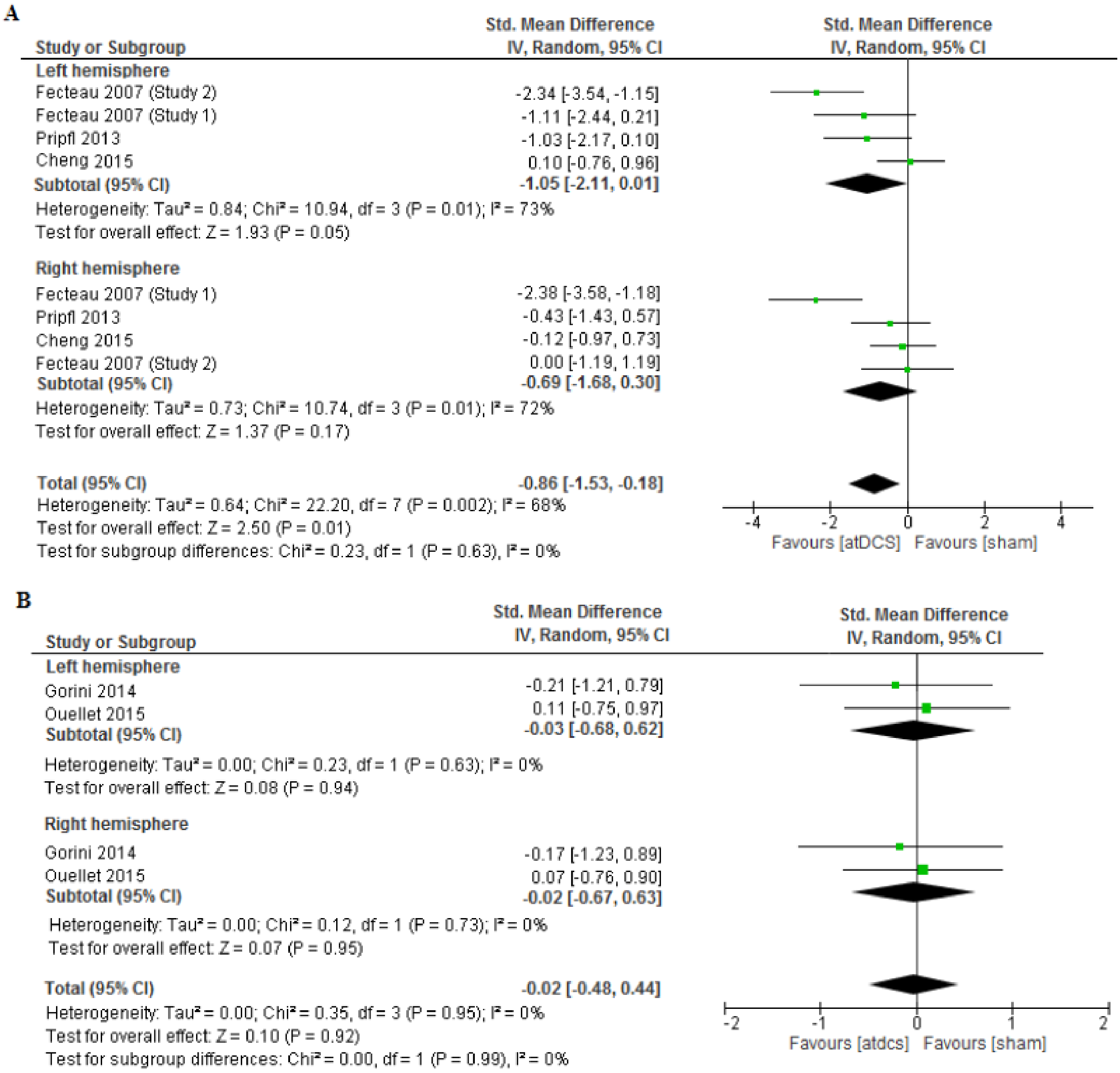


Figure 4.2. Forest plot of the effect of tDCS on risk-taking behaviour in the Balloon Analogue Risk Task (BART) and Columbia Card Task (CCT). Panel A shows studies in which risk-taking performance was measured during online stimulation. Panel B shows studies in which risk-taking performance was measured offline following stimulation. Online tDCS to the left DLPFC was associated with a significant medium effect size in reducing risk-taking performance, while online tDCS to the right DLPFC and offline tDCS did not show a significant effect. The overall effect of online tDCS was attributable to the effect on the left DLPFC.

4.8.2.2 TDCS effects on Type 1 decision-making

A total of 5 studies (Votinov et al., 2013; Votinov et al., 2013; Sellaro, Derks, et al., 2015; Sellaro, Güroğlu, et al., 2015; Ly et al., 2016; Oldrati et al., 2016) were categorised as measuring Type 1 processing (i.e., resulting intuitive or biased answers) during stimulation. There were no offline tDCS studies found in the meta-analysis involving the right hemisphere. The overall comparison of the effect sizes in these studies revealed no effect of stimulation on accuracy (SMD = -0.33, 95% CI = -10, 0.32, p = 0.32) compared to sham across left and right hemispheres.

For the 3 studies that used tDCS over the left frontal lobe (Votinov et al., 2013; Sellaro, Derks, et al., 2015; Ly et al., 2016) the analysis revealed that stimulation was associated with a significant improvement in accuracy (SMD = -0.6, 95% CI = -1.04, 0.15, p = 0.01) compared to sham. There was no effect of anodal tDCS over the right DLPFC (Votinov et al., 2013) (SMD = -0.10, 95% CI = -0.71, 0.95, p = 0.82). Only accuracy scores were used for the meta-analysis.

The one study that used offline anodal tDCS to the left DLPFC found no improvement in accuracy (Oldrati et al., 2016) (SMD = 0.13, 95% CI = -0.64, 0.90, p = 0.74) compared to sham. One study (Sellaro, Derks, et al., 2015) used offline tDCS over medial prefrontal cortex (at FPz) so was not included the left or right hemisphere analyses.

4.8.2.3 TDCS effects on Type 2 decision-making

In this category, a total of 8 studies (Hecht et al., 2010; Minati et al., 2012; Hecht et al., 2013; Ye et al., 2015a 2015b; Mengarelli et al., 2015; Colombo et al., 2016; Oldrati, et al., 2016) met the criterion of the author (i.e., aiming to improve normative decision-making performance). The overall comparison of the effect sizes of the 4 studies in 4 articles with online tDCS collapsed across hemispheres (Hecht et al., 2010; Minati et al., 2012; Hecht et al., 2013; Mengarelli et al., 2015) revealed no effect of stimulation on accuracy (SMD = 0.53, 95% CI = -0.60, 1.66, p = 0.36) compared to sham. The overall comparison of the effect sizes of the 4 studies in 2 articles using offline tDCS (Ye et al., 2015a; 2015b; Oldrati et al., 2016) also revealed no effect of stimulation on accuracy (SMD = -0.42, 95% CI = -1.50, 0.67, p = 0.45). All behavioural measures for this analysis were accuracies.

Looking at the online stimulation studies only, the effect size analysis of the 4 individual studies (Hecht et al., 2010; Minati et al., 2012; Hecht et al., 2013; Mengarelli et al., 2015) revealed that left DLPFC online anodal tDCS was not associated with any changes in accuracy (SMD = 0.85, 95% CI = -0.60, 2.30, p = 0.25) compared to sham. There was also no effect of online anodal tDCS over the right DLPFC (Hecht et al., 2010 Minati et al., 2012) (SMD = -0.11, 95% CI = -0.96, 0.74, p = 0.82). One behavioural measure for this analysis was a percentage of choice score between two alternatives (Hecht et al., 2013), all other measures were accuracy scores.

For the offline stimulation studies only, the effect size analysis of the 3 studies using anodal tDCS over the left DLPFC (Ye et al., 2015a; 2015b; Oldrati et al., 2016) revealed no improvement in accuracy (SMD = -0.57, 95% CI = -2.15, 1.02, p = 0.48) compared to sham. As only one study applied offline anodal tDCS over the right DLPFC (Ye et a., 2015a), effect size analysis was not possible. All behavioural measures were accuracies.

4.8.2.4 Combined effects of anodal tDCS on decision-making and risk-taking

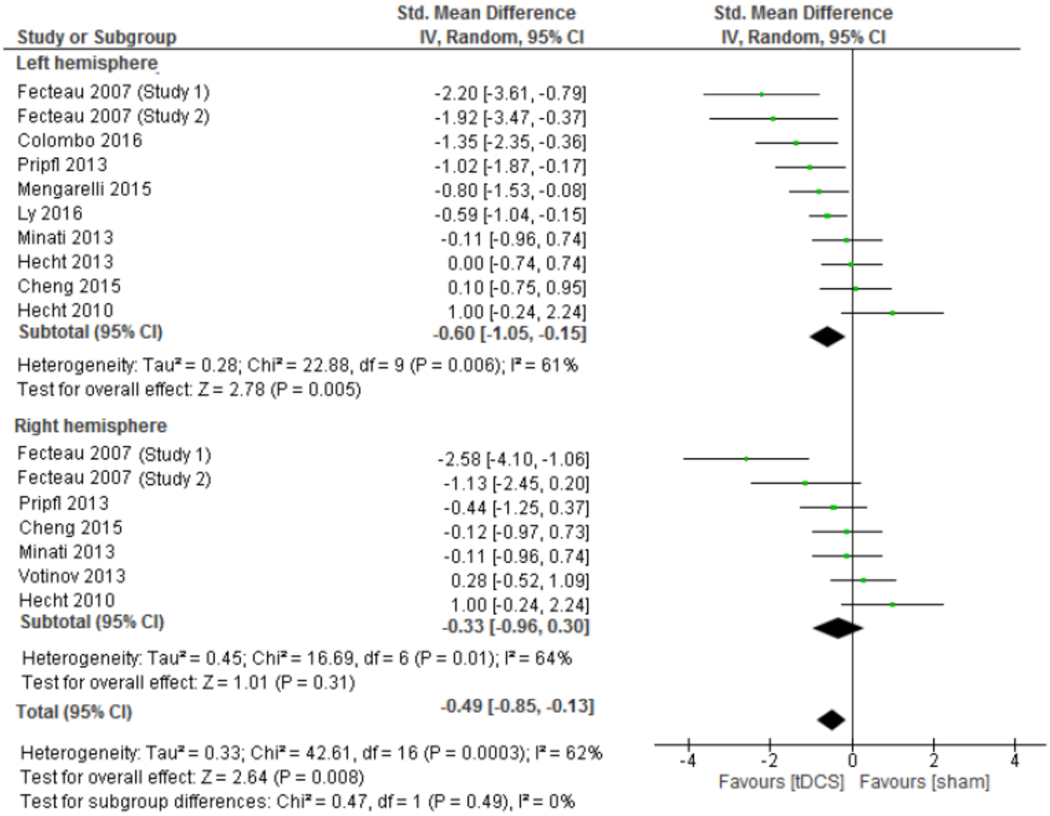
An omnibus comparison of the effect sizes of all included studies after collapsing the data across tasks revealed that online stimulation (Fecteau et al., 2007 – two studies; Hecht et al., 2010; Hecht et al. 2013; Minati et al., 2013; Pripfl et al., 2013; Votinov et al., 2013; Cheng & Lee, 2015; Mengarelli et al., 2015; Colombo et al., 2016; Ly et al., 2016) was associated with improved decision-making accuracy and reduced risk-taking behaviour (SMD = -0.5, 95% CI = -0.85, -0.13, p = 0.01; 8 studies in total). For offline stimulation (Gorini et al., 2014; Ouellet al., 2015; Ye et al., 2015a; 2015b; Oldrati et al., 2016) there were no statistically significant effects (SMD = -0.14, 95% CI = -0.78, 0.50, p = 0.66; 6 studies in 5 articles) (Figure 4.3). All behavioural measures for this analysis were accuracies.

Looking at the online stimulation studies only, the 10 studies from 9 articles (Fecteau et al., 2007 – two studies; Hecht et al., 2010; Hecht et al. 2013; Minati et al., 2013; Pripfl et al., 2013; Cheng & Lee, 2015; Mengarelli et al., 2015; Colombo et al., 2016; Ly et al., 2016) targeting the left DLPFC only revealed a significant increase in decision-making accuracy and decreased risk-taking behaviour (SMD = -0.60, 95% CI

= -1.05, -0.15, p = 0.01) as compared to sham tDCS. This was largely due to studies that captured Type 1 thinking and risk decision-making (Cheng & Lee, 2015; Ly et al. 2016). However, the 6 studies targeting the right DLPFC (Fecteau et al, 2007; Hecht et al., 2010; Minati et al, 2013; Pripfl et al., 2013; Votinov et al., 2013; Cheng & Lee, 2015)) found no effect of stimulation on accuracy in these tasks (SMD = -0.33, 95% CI = -0.96, 0.30, p = 0.31) compared to sham.

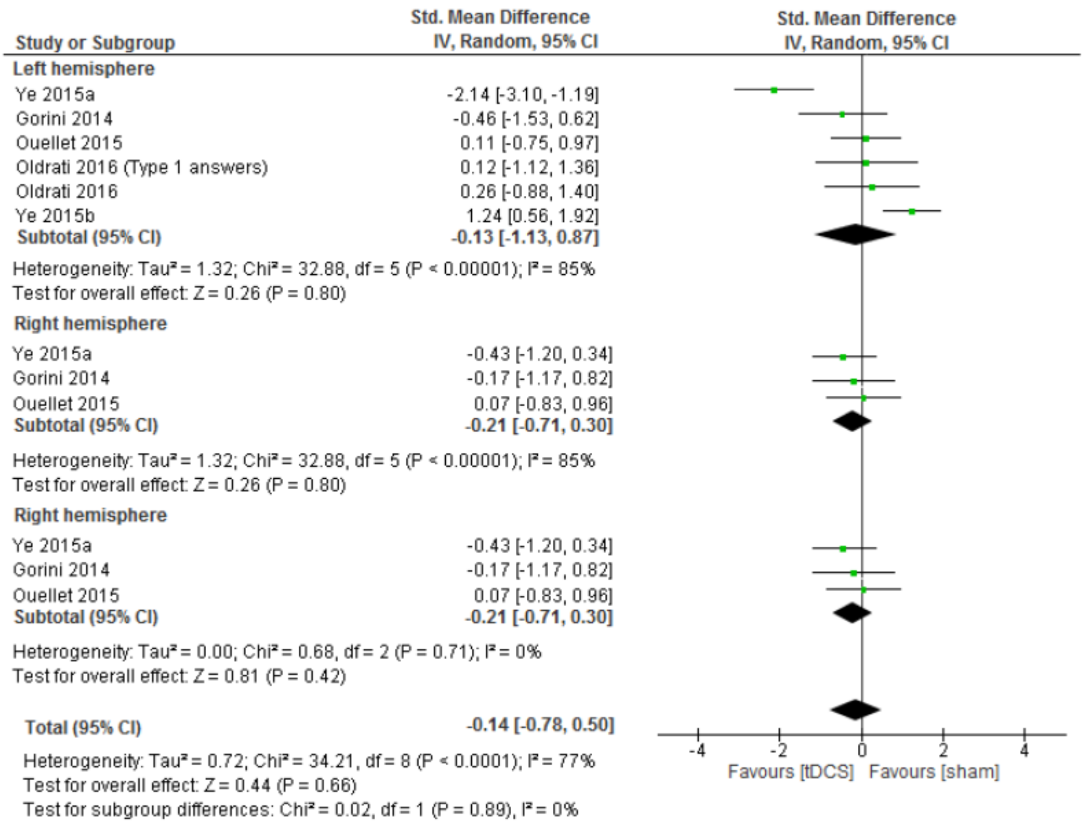
For the 9 studies using offline stimulation (Gorini et al., 2014; Ouellet al., 2015; Ye et al., 2015a; 2015b; Oldrati et al., 2016), there was no statistically significant effect of stimulation on decision-making for either hemisphere. Of these 6 studies in 5 articles (Gorini et al., 2014; Ouellet et al., 2015; Ye et al., 2015a; 2015b; Oldrati et al., 2016 – 2 studies) were stimulating the left DLPFC (SMD = -0.13, 95% CI = -1.13, 0.87, p = 0.80) and found no effect of stimulation on decision-making. Whilst the 3 studies (Gorini et al., 2014; Ouellet et al., 2015; Ye et al. 2015a) targeting the right DLPFC were not associated with any significant effects of stimulation on decision-making (SMD = -0.21, 95% CI = -0.71, 0.30, p = 0.42) as compared to sham tDCS. All behavioural measures for the analysis were accuracies.

A



Std. Mean Difference
IV, Random, 95% CI
Study or Subgroup
Std. Mean Difference
IV, Random, 95% CI
Left hemisphere
Fecteau 2007 (Study 1) -2.20 [-3.61, -0.79]
Fecteau 2007 (Study 2) -1.92 [-3.47, -0.37]
Colombo 2016 -1.35 [-2.35, -0.36]
Pripfl 2013 -1.02 [-1.87, -0.17]
Mengarelli 2015 -0.80 [-1.53, -0.08]
Ly 2016 -0.59 [-1.04, -0.15]
Minati 2013 -0.11 [-0.96, 0.74]
Hecht 2013 0.00 [-0.74, 0.74]
Cheng 2015 0.10 [-0.75, 0.95]
Hecht 2010 1.00 [-0.24, 2.24]
Subtotal (95% CI) -0.60 [-1.05, -0.15]
Heterogeneity: Tau² = 0.28; Chi² = 22.88, df = 9 (P = 0.006); I² = 61%
Test for overall effect: Z = 2.78 (P = 0.005)
Right hemisphere
Fecteau 2007 (Study 1) -2.58 [-4.10, -1.06]
Fecteau 2007 (Study 2) -1.13 [-2.45, 0.20]
Pripfl 2013 -0.44 [-1.25, 0.37]
Cheng 2015 -0.12 [-0.97, 0.73]
Minati 2013 -0.11 [-0.96, 0.74]
Votinov 2013 0.28 [-0.52, 1.09]
Hecht 2010 1.00 [-0.24, 2.24]
Subtotal (95% CI) -0.33 [-0.96, 0.30]
Heterogeneity: Tau² = 0.45; Chi² = 16.69, df = 6 (P = 0.01); I² = 64%
Test for overall effect: Z = 1.01 (P = 0.31)
Total (95% CI) -0.49 [-0.85, -0.13]
Heterogeneity: Tau² = 0.33; Chi² = 42.61, df = 16 (P = 0.0003); I² = 62%
Test for overall effect: Z = 2.64 (P = 0.008)
Test for subgroup differences: Chi² = 0.47, df = 1 (P = 0.49), I² = 0%
-4 -2 0 2 4
Favours [tDCS] Favours [sham]

B



Std. Mean Difference
IV, Random, 95% CI
Study or Subgroup
Std. Mean Difference
IV, Random, 95% CI
Left hemisphere
Ye 2015a -2.14 [-3.10, -1.19]
Gorini 2014 -0.46 [-1.53, 0.62]
Ouellet 2015 0.11 [-0.75, 0.97]
Oldrati 2016 (Type 1 answers) 0.12 [-1.12, 1.36]
Oldrati 2016 0.26 [-0.88, 1.40]
Ye 2015b 1.24 [0.56, 1.92]
Subtotal (95% CI) -0.13 [-1.13, 0.87]
Heterogeneity: Tau² = 1.32; Chi² = 32.88, df = 5 (P < 0.00001); I² = 85%
Test for overall effect: Z = 0.26 (P = 0.80)
Right hemisphere
Ye 2015a -0.43 [-1.20, 0.34]
Gorini 2014 -0.17 [-1.17, 0.82]
Ouellet 2015 0.07 [-0.83, 0.96]
Subtotal (95% CI) -0.21 [-0.71, 0.30]
Heterogeneity: Tau² = 1.32; Chi² = 32.88, df = 5 (P < 0.00001); I² = 85%
Test for overall effect: Z = 0.26 (P = 0.80)
Right hemisphere
Ye 2015a -0.43 [-1.20, 0.34]
Gorini 2014 -0.17 [-1.17, 0.82]
Ouellet 2015 0.07 [-0.83, 0.96]
Subtotal (95% CI) -0.21 [-0.71, 0.30]
Heterogeneity: Tau² = 0.00; Chi² = 0.68, df = 2 (P = 0.71); I² = 0%
Test for overall effect: Z = 0.81 (P = 0.42)
Total (95% CI) -0.14 [-0.78, 0.50]
Heterogeneity: Tau² = 0.72; Chi² = 34.21, df = 8 (P < 0.0001); I² = 77%
Test for overall effect: Z = 0.44 (P = 0.66)
Test for subgroup differences: Chi² = 0.02, df = 1 (P = 0.89), I² = 0%
-4 -2 0 2 4
Favours [tDCS] Favours [sham]

Figure 4.3. Forest plot of effects of stimulation on all tasks in this systematic review. Panel A shows studies in which performance was measured during online stimulation. Panel B shows studies in which performance was measured offline following stimulation. Only studies with left hemisphere online stimulation showed an overall significant effect of tDCS on performance. All studies regardless of site of hemisphere stimulation with online stimulation showed a significant large effect size of tDCS on performance.

4.9 Discussion

The present systematic review and meta-analysis investigated whether tDCS neuromodulation affects decision-making performance, including risk-taking. Across tasks, non-invasive tDCS over the dorsolateral prefrontal cortex showed an effect in modulating behaviour, but only for task-completion during stimulation, and significantly only for the left hemisphere (although there were trends for right stimulation effects also). This pattern was mirrored at the level of groups of tasks. For risk-taking only online tDCS to the left DLPFC or collapsed across both hemispheres was associated with reduced risk-taking behaviour. Similarly, for tasks that tapped Type 1 decision-making (or collapsed across Type 1 and Type 2), only online anodal stimulation to the left frontal lobe – or again across both hemispheres - increased decision-making performance. There were no significant effects of either online or offline tDCS on Type 2 decision-making alone.

The proposed mechanism behind successful manipulation of decision performance via tDCS of the left DLPFC is that tDCS alters other cognitive functions that are associated with decision-making, such as working memory (updating) (Evans &

Stanovich, 2013), attention (Goel & Vartanian, 2004) and impulsivity (Ye et al., 2015a). Furthermore, the left DLPFC has been suggested to be important in self-regulation processes (Mengarelli et al. 2015) and affective modulation (Hare et al., 2009). In contrast, the right DLPFC has been suggested to be involved in impulsivity (Loftus et al., 2015), and to have a critical role in set-shifting (the manipulation of mental models) in problem solving, reasoning and planning (Loftus et al., 2015).

One possible explanation for the reduction in decision-making bias and improvement in accuracy is that the left DLPFC is involved in the cognitive control of prepotent and impulsive responses in decision-making (Aron, Robbins, & Poldrack, 2004; Stagg & Nitsche, 2011). This region supports the convergence of interconnections with other brain structures that in turn coordinate complex behaviour such as planning, decision-making and problem solving (Hecht et al., 2010; Cheng & Lee, 2015). Anodal tDCS to the left DLPFC may increase activity in the neural populations that are crucial for the integration of signals involved in the cognitive control of decision-making (André Russowsky Brunoni & Vanderhasselt, 2014). More specifically, anodal stimulation of the left DLPFC has been found to significantly reduce reaction times and error rates for incongruent items in the Stroop inhibitory test (Aron et al., 2004), thereby improving control over the prepotent responses, compared to sham. Here, the reviewed decision-making tasks measure something similar: just in how far participants overcome pre-potent (biased) responses to arrive at correct answers. By this logic improved Type 1 decision-making may be a result of online stimulation because of the 'fast' automatic nature of processes that have to be overcome just as in the Stroop task. The question then remains is as to why we saw no increase for Type 2 performance?

Rather than just relying on successful inhibition, Type 2 processes also rely on a participants' ability to simulate certain situations or outcomes (Evans, 2003). This is achieved by mapping the encountered world onto a primary representation, whilst a copy of it (a secondary representation) can be successfully 'decoupled' and mentally manipulated. Working memory performance is a potential measure of this ability for mental simulation. Dual-process frameworks (Evans, 2003; 2008) typically link working memory performance with increased decision-making performance, and in a meta-analysis, Hill et al., (2016) found an improvement in working memory performance during offline stimulation. However, there was a failure to show any improvements in tasks that may have benefitted from Type 2 simulation processes. One reason for the lack of overall significant effect of stimulation may be that most of the studies that were included in the Type 2 analysis used online stimulation rather than offline stimulation, whereas the current analyses mainly obtained significant effects of neuromodulation on decision-making during offline stimulation (experiments 1 to 3). Alternatively, the potential relationship between working memory processes and analytical decision-making in the left DLPFC may be more complex than some of the dual-process models state (Evans, 2003; 2008).

Online tDCS applied to the left prefrontal cortex, namely to the DLPFC, also significantly reduced risk-taking behaviour. However, online tDCS applied to the right prefrontal cortex and offline tDCS to the right prefrontal cortex, did not improve risk-taking. The differences in tDCS effects between online and offline stimulation can be explained by the functional differences in underlying mechanisms of these types of stimulation (Nitsche et al., 2003; Caumo et al., 2012).

The functional specificity of online and offline tDCS can be explained in two ways (Nitsche et al., 2003; Priori, 2003). Online stimulation is dependent on changes in the membrane potential during task performance: the effect of stimulation on task-relevant neurons boosts the already heightened activity of these neuron populations (Aron et al., 2004). At the cellular level, online anodal stimulation alters the membrane potential of neurons by depolarizing neurons by increasing Na+ (sodium) influx into the cell (Liebetanz et al., 2002). The result of the influx of sodium ions (Na+) is evident when Na+ channel antagonists, such as carbamazepine, block the effect of anodal stimulation during the stimulation (Liebetanz et al., 2002).

Conversely, offline stimulation, is driven by changes in synaptic strength (Nitsche et al., 2003). This, involves the modulation of glutamatergic activity through the potentiation of synaptic glutamatergic receptors, which in turn has an effect on neuronal populations independent of task performance (Nitsche et al., 2003; 2008). The neuroplastic changes from offline stimulation is similar to those of long-term potentiation (LTP) and long-term depression (LTD) in that the GABAergic and glutamatergic systems are both implicated in LTP, LTD and after effects of offline stimulation (Stagg et al., 2009; Dayan et al., 2013).

One limitation of this review concerns the methodological differences in each of the articles that have been included (e.g., duration of tasks, number of trials etc). If one takes the BART as an example there were differences in the number of trials and total durations of some of the studies (Fecteau, Pascual-Leone, et al., 2007; Hecht et al., 2010). The second limitation is that with the exception of the BART there was little uniformity between the tasks included in this review, for example, there were not enough studies combining any of the heuristics with tDCS to conduct a larger analysis.

Taken together with the omnibus and risk-taking meta-analyses that were conducted in this review this suggests that left DLPFC is involved in the modulation of decision-making bias. Increasing cortical excitability by depolarizing the neuronal membranes in the left DLPFC increased accuracy compared to sham. When combined with the literature on neuromodulation of the Stroop task (Aron et al., 2004) this may indicate that increasing cortical excitability in the left DLPFC moderates the inhibitory mechanisms that are involved the Stroop and in decision-making. However, this needs to be empirically tested in experiments that combine neuromodulation with judgement and decision-making tasks (e.g., the CRT), and crucially, executive function tasks (e.g., the Stroop) - the following experiments does so.

4.10 Summary

This systematic review and meta-analysis of the literature of tDCS neuromodulation and decision-making revealed that only online stimulation modulates decision-making. Online stimulation of the left frontal lobe modulates decision-making tasks that tap Type 1, intuitive thinking. Furthermore, only online tDCS of the left DLPFC was sufficient to alter risk-taking behaviour, reducing risk-taking. This review was limited in two ways - firstly, by the small number of publications that use tDCS neuromodulation with decision-making, and secondly, by the lack of a single consistent experimental task that is used across these studies that taps either Type 1 or Type 2 thinking.

Chapter 5

Experiment 1: The effect of tDCS neuromodulation of the right dorsolateral prefrontal cortex on risk-taking, working memory performance, and cognitive reflection.

5.1 Background

As reviewed in Chapter 3, executive functions are crucial to judgement and decision-making. The crucial executive functions in decision-making are updating, inhibition and set-shifting (Miyake et al., 2000; Miyake & Friedman, 2012). Inhibition and updating are examined in this experiment. To override automatic Type 1 processing with analytic Type 2 processing one must inhibit the former in favour of the latter (De Neys, 2006; Stanovich, 2009). At the same time, high working memory capacity (updating) is needed when using Type 2 (but not for Type 1) processing (Evans, 2006; 2012).

A brain region of interest for executive functioning and decision-making processes that tap the dual-process framework is the dorsolateral prefrontal cortex (DLPFC) which has been reliably associated with these decision-making processes (Dockery et al., 2009; Tayeb & Lavidor, 2016). More specifically, a lateralization has been suggested: the left DLPFC is involved in self-regulation (Mengarelli et al., 2015), affective modulation (Hare et al., 2009) and attentional processing (Goel et al., 2006), whilst the right DLPFC has a role in impulsivity control (Loftus et al., 2015), cognitive control (Santarnecchi, Rossi, & Rossi, 2015) and set-shifting (i.e., the manipulation of mental models) (Loftus et al., 2015). The latter two aspects of cognitive processing are conceived of as important executive functions (Miyake et al., 2000), which are implicated in judgement and decision-making performance (e.g., Type 2 processing, (Evans & Curtis-Holmes, 2005; Toplak, West, & Stanovich, 2011).

In Experiment 1, the effect of tDCS on performance in cognitive reflection and judgement tasks was examined. In addition, a series of belief bias syllogisms were used that consist of two short premises and a conclusion which vary in congruence with prior beliefs, differing in whether there was a conflict or no conflict between logic and belief (De Neys, 2006; Trippas, Verde, & Handley, 2014). One measure obtained by the belief-bias is the so-called logic index, indicating a participant's ability to reason using presumably mental simulation: the ability to maintain and symbolically manipulate separate mental representations of a problem (Stupple, Ball, Evans, & Kamal-Smith, 2011; Stupple, Ball, & Ellis, 2013). Some approaches in the dual-process framework (e.g., Stanovich, West, & Toplak, 2013) implicate mental simulation performance with successful Type 2 processing (in addition to inhibition performance).

In a within-subjects design decision-making was measured following twenty minutes of anodal tDCS (a-tDCS) over the right DLPFC or sham. It was hypothesised that increasing the cortical excitability of the right DLPFC would boost Type 2 performance, in particular inhibition performance, thus increasing cognitive reflection scores and reducing heuristic thinking in the heuristics and biases tasks. For the syllogistic reasoning it was predicted that the logic index should be affected by stimulation, but here performance would be less reliant on inhibition (right DLPFC). Crucially, the prediction is that if Type 1 processing is dissociable from Type 2 processing

(Stanovich, 2013) then one would predict that only the right DLPFC would benefit performance scores. In short, where Oldrati et al., (2016) stimulation studies aimed to increase Type 1 responses, our study aimed to test whether right anodal DLPFC stimulation increases Type 2 responses.

5.2 Research questions

It was asked whether the intuitive thinking (Type 1), cognitive reflection (Type 2), inhibition (Numerical Stroop), risk-taking behaviour (BART) and working memory (2-back) are modified by anodal tDCS of the right dorsolateral prefrontal cortex (right DLPFC). Furthermore, it was asked how any modulation of the aforementioned influences decision processes in the dual-processing framework of decision-making.

Research question 1

Does online anodal tDCS of the right DLPFC affect decision-making bias (belief bias, heuristics and biases battery)?

Prediction 1: anodal stimulation of the right DLPFC will decrease decision-making bias as shown by higher accuracy scores during stimulation for the belief bias and heuristics and biases battery compared to sham.

Research question 2

Does online anodal tDCS of the right DLPFC affect cognitive reflection as measured by the Cognitive Reflection Test (CRT)?

Prediction 2: anodal stimulation of the right DLPFC will increase CRT performance as shown by higher accuracy during stimulation compared to sham.

Research question 3

Does offline anodal tDCS of the right DLPFC affect working memory (i.e., updating) as measured by the 2-back?

Prediction 3: offline anodal stimulation of the right DLPFC will increase working memory performance as shown by higher accuracy in the 2-back after stimulation compared to sham.

Research question 4

Does offline anodal tDCS of the right DLPFC affect the inhibition of pre-potent responses in the numerical Stroop?

Prediction 4: offline anodal stimulation of the right DLPFC will increase inhibitory control of pre-potent responses as shown by higher accuracy in the numerical Stroop after stimulation compared to sham.

Research question 5

Does offline anodal tDCS of the right DLPFC affect risk-taking behaviour as measured by the Balloon Analogue Risk Task (BART)?

Prediction 5: offline anodal stimulation of the right DLPFC will decrease risk-taking performance as shown by lower BART scores after stimulation compared to sham.

5.3 Methodology

5.3.1 Design

This experiment adopted a within-subjects design. The independent between-subjects variable was stimulation group (anodal right DLPFC or sham). Stimulation began immediately before the start of the behavioural tasks and continued for the duration of the first block of tasks only, lasting twenty minutes in total (online tasks) (Figure 5.1). A second block of offline tasks were completed after stimulation ended lasting approximately thirty minutes. The total time of stimulation and current intensity (1.5mA) was within the safety recommendations and standard experimental protocols (Nitsche et al., 2003). No participant reported adverse effects of tDCS. Sham and experimental conditions were randomised. All tasks were counterbalanced within each block. It was not possible to counterbalance block 1 with block 2 as one cannot have offline stimulation before online stimulation. As the main tasks of interest for this experiment were the decision-making tasks these remained in the online stimulation block throughout the experiment.

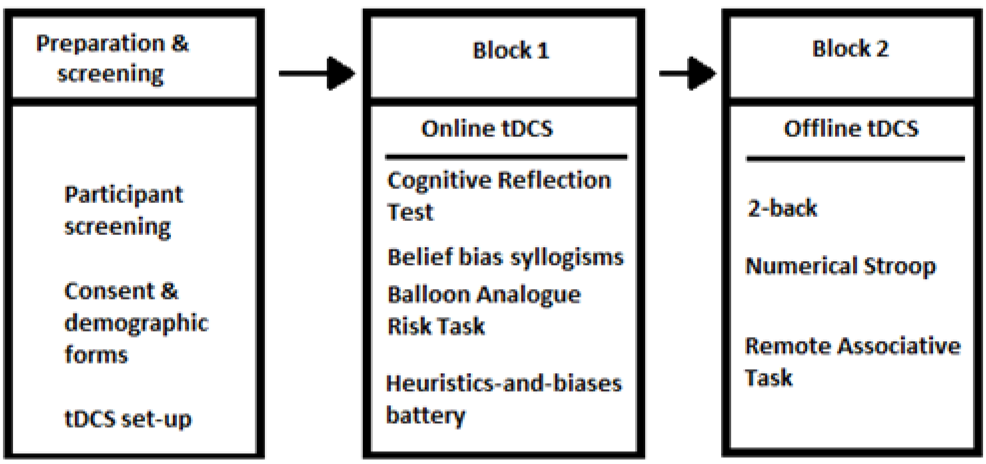


Figure 5.1. Block procedure of this experiment. Arrows denote time course. The Cognitive Reflection Test, belief bias syllogisms, heuristics and biases battery (containing

representativeness vignettes) and Balloon Analogue Risk Task were issued to participants during stimulation (online) in block 1. The 2-back, numerical Stroop and Remote Associative Task were use after the cessation of stimulation (offline) in block 2. All tasks were counterbalanced during data collection.

5.3.2 Participants

Thirty participants were recruited through advertising and word-of-mouth on campus at The University of East London (mean age = 29.47 ± 7.35 years; mean; 21 females). Participants attended two sessions at approximately the same time of day in consecutive weeks due to circadian factors as a source of noise (Ridding & Ziemann, 2010). Each of these sessions were counterbalanced across participants, including sham.

A power analysis calculation using G Power 3.0 revealed that a sample size of 18 participants was needed to reach a significant result. This was based on a medium effect size of $f = 0.30$, according to the convention set out by Cohen (1969, p348), and an alpha (α) significance level of $p = 0.05$ in a within-subjects design experiment with a total of 6 measures and 2 conditions.

The inclusion criteria were (i) aged 18 years or above; (ii) fluent English speakers; (iii) right-handed; (iv) naïve to tDCS and (v) naïve to the behavioural tasks used. The exclusion criteria were (i) history of seizures; (ii) family history of seizures; (iii) past or present neurological history; (iv) past or present psychiatric history; (v) part head injury or surgery; (vi) metal implants; (vii) current medication usage; (viii) drug or alcohol dependence; (ix) pregnancy and (x) past training in logic during a university course.

All participants gave informed written consent before entering the study, which was approved by The University of East London (UEL) Research Ethics Committee. After giving consent participants completed a demographic form containing information about sex (male, female or do not wish to say), age, religiosity (yes or no), paranormal beliefs (yes or no) and education level – self reported highest current education level (Table 5.1). Participants were asked about religiosity based on the dual-process framework literature that suggest that high levels of religiosity positively correlates with high levels of intuitive thinking on the CRT (Pennycook et al., 2012; Razmyar & Reeve, 2013).

Table 5.1. Demographics and cognitive characteristics.

Demographic variable	
Sex (F/M)	21/9
Age	29.47 (7.35)
Religious (Yes/No)	15/15
Paranormal belief (Yes/No)	17/13
Education	6.03 (1.00)

Education represents qualification level. Abbreviations: Standard Deviations (SD), females (F), males (M).

5.3.3 tDCS montage and parameters

TDCS was delivered using a battery-driven stimulator device (Neuroelectrics, Barcelona) using two sponge electrodes (anodal and return) each circular with a surface area of 25cm^2. Electrodes were soaked in a saline solution. Skin preparation and electrode placement were in accordance with established procedures. The tDCS montage was dependent upon the stimulation condition (anodal electrode – return electrode): (i) right DLPFC left DLPFC or (ii) sham condition. The electrodes were placed over the F4 (for right DLPFC) or / and F3 (for left DLPFC) according to the EEG 10-20 international system.

Throughout this thesis the convention of referring to the tDCS electrode that is not at the stimulation site of interest (i.e., the right DLPFC in this experiment) as the return electrode is used (Woods et al., 2016). This convention is used here as it disingenuous to discuss either 'anodal tDCS' or 'cathodal tDCS' without referring to the presence of the return electrode, as assuming that the current flow beneath any electrode into the cortex is simply unidirectional (without considering brain morphology) is misleading (Bikson et al., 2011; Antal et al., 2017).

In the stimulation condition a constant current of 1.5mA was administered for twenty minutes. There was a gradual increase and decrease of 15 seconds each at the onset of offset of stimulation to decrease the likelihood of discomfort. For sham, the two electrodes were placed over F3 and F4 but stimulation only became active for the 30 second duration of the onset and offset, after which the stimulation ceased and the electrodes remained in place.

The sham procedure (with an identical electrode montage to the experiment condition) was in line with previous procedures and has been shown to be effective in inducing the slight tDCS-associated physiological sensations such as a tingling feeling which last for a few seconds during real stimulation (Ambrus et al., 2012).

Due to time constraints during data collection and laboratory consumable resources (i.e., funding for the payment of participants) it was not possible to run a third experimental group as an active control group. The addition of an active control in an experiment in which the main experimental group involves the stimulation of the right DLPFC would involve the anodal stimulation of an area such as the occipital lobe with the return (reference) electrode over the right DLPFC. Experiment 2 (Chapter 6) contains an experimental group with the opposite polarity to the experimental group in this experiment, as such this in part excludes the need for an active control group.

After the completion of the judgement and decision-making tasks all of the electrodes were removed and the remaining tasks began (i.e., during offline stimulation). This procedure was chosen because it has been previously shown to be effective in reducing risk-taking (Fecteau, Knoch, et al., 2007; Cheng & Lee, 2015).

5.3.4 Materials and measures

All materials and measures used in this study were established tasks from the literature (see Appendix A). The Cognitive Reflection Test (CRT) (Oldrati et al., 2016), Balloon Analogue Risk Task (BART) (Cheng & Lee, 2015), n-back (Hill et al., 2016) and belief bias syllogisms (Tsujii, Sakatani, Masuda, Akiyama, & Watanabe, 2011) have been used in previous neuromodulation studies. The heuristics and biases battery, including representativeness, availability, framing, sample size, sunk cost, outcome and ratio biases with the conjunction and gambler's fallacy have been used in the judgement and decision-making literature but not with neuromodulation prior to this study (Toplak et al., 2011; Oldrati et al., 2016). For details and examples of each of these heuristics and biases, other than the representativeness vignettes, see appendix A. The representativeness vignette description is below.

5.3.4.1 Online tasks

The Cognitive Reflection Test (CRT) (detailed in Chapter 4, page 64) and Balloon Analogue Risk Task (BART; detailed in Chapter 4, page 65) were administered in this study. The CRT consisted of a total of 6 items, split into 2 parts of 3 items and given to participants over the 2 testing sessions. There was a maximum score of 3 per session. The number of items for the CRT was motivated by the limited number of CRT items available at the time of data collection for Experiment 1 – a total of 7 items from Frederick (2005) and Toplak et al., (2011). As 7 items could not be split into two equal parts the 'Bat and Ball' item was excluded from Experiment 1. The BART contained a practice of 10 trials, before starting a total of sixty balloon trials per experimental session.

Heuristic-and-bias battery (including representativeness).

Heuristics and biases are decision-making aids that require little effort or cognitive resources to use (Amos Tversky & Kahneman, 1973; Toplak et al., 2011). These heuristics rely on the automatic process of Type 1 thinking. Participants saw short vignettes or questions that have been used in the heuristics and biases literature before and choose a response.

A total of fifteen heuristics and biases were issued to participants per session on a computer and the ten ratio bias items were administered on paper. The heuristics and biases were the availability heuristic (2 items), conjunction fallacy (2 items), framing bias (2 items), gambler's fallacy (1 item), outcome bias (2 items), representativeness heuristic (3 items), sample size bias (1 item), and the sunk cost bias (2 items).

Representativeness (incongruent base-rate) vignettes: The representativeness heuristic, also called incongruent base-rate vignettes (Grether, 1980; Teigen & Keren, 2007) shows that when presented with base-rate information (e.g., the probability of independent events or attributes occurring) and specific information (i.e., a stereotype of an occupation) participants ignore the former in favour of the latter (Kahneman & Tversky, 1973; Teovanović, Knežević, & Stankov, 2015).

As mentioned above (under the heuristics and biases section) a total of 3 representativeness vignettes were issued to participants per session.

Belief bias syllogisms: Belief bias syllogisms are a behavioural measure of the susceptibility of logic to interference from believability (Evans & Curtis-Holmes, 2005). Participants view two premises (e.g., ALL ROSES NEED WATER and PLANTS NEED WATER) with a conclusion (e.g., THEREFORE, ROSES ARE PLANTS). Participants must respond by deciding if they accept the conclusion (Čavojová, 2015).

At analysis responses were transformed to indicate if participants accepted or did not accept the conclusion (from whether they thought the conclusion was valid or invalid) using the following indices. For scoring and subsequent parametric analyses, a logic index and a belief index were calculated (Stupple et al., 2011; 2013). The logic index is the difference between the acceptance of valid and invalid conclusions, with larger indices being indicative of greater belief bias. The belief index is the difference between the acceptance of believable and unbelievable conclusions, with large indices indicating greater belief bias.

A total of sixteen belief bias syllogisms were administered to participants per session. There were 4 syllogisms for each of the following types of syllogisms: valid-believable, valid-unbelievable, invalid-believable, and invalid-unbelievable.

5.3.4.2 Offline tasks

n-back

The n-back is a behavioural measure of working memory capacity (Kirchner, 1958; Jaeggi, Buschkuehl, Perrig, & Meier, 2010). Working memory capacity is measured by presenting a continuous sequence of stimuli with a load factor of '*n'* that can be adjusted to make the task harder or easier (Jaeggi et al., 2010). The stimuli consist of a single letter (e.g., A or B) in the centre of a computer monitor. Participants are instructed to remember the sequence of letters and report any repetitions with the load factor *n*. In the 2-back that was used in this study the load factor was 2 (2-back). Participants responded to letters that had been repeated 2 steps before (e.g., T L H C O **K** I **K**).

Five practice trials preceded a total of thirty main trials per experimental session.

Numerical Stroop

The numerical Stroop is a variant of the original colour-word Stroop (Stroop, 1935; Besner & Coltheart, 1979; Girelli, Sandrini, Cappa, Butterworth, 2001). Participants view an instruction that says to report either the number of words (e.g., 3 = ONE ONE ONE) or the value of words (e.g., 2 = TWO). Only the words / numbers 'One', 'Two' and 'Three' were used during this task. Word stimuli were presented in the centre of the screen for one second each in sequence that consisted of thirty incongruent and thirty congruent words. Each condition (incongruent or congruent) were counterbalanced.

Before starting this task, participants completed 5 practice trials ensure that they understood the instructions. A total of thirty main trials were then administered to participants per session. Although this task was administered during Experiment 1 this was not analysed due to programming issues.

Remote Associative Test (RAT)

The Remote Associative Test (RAT) was originally designed to measure creativity (Mednick, Mednick, & Mednick, 1964). In the decision-making literature the RAT has been adapted to measure insight (Suzuki & Usher, 2009; Yang, Yang, & Isen, 2013). Participants view a triad of words (e.g., CREAM, AFTERNOON and CLOTH) and must think of a forth word that can connect the triad together (e.g., TEA). The word that the participant thinks of can go before or after each of the triad words (e.g., CREAM TEA, AFTERNOON TEA or TEA CLOTH).

A total of ten-word pairs were administered to participants per session as a paper and pen task. Participants were limited to a maximum duration of ten minutes for the RAT. Answers were classified in terms of accuracy across the ten-word pairs.

No decision-making tasks were administered to participants more than once across this experiment. All data collection recorded in Experiment was based on accuracy rather than reaction time. Accuracy was chosen here without reaction time because the administration of the CRT in Experiment 1 was done through paper and pen.

5.4 Results

The raw data were screened for outliers and missing values before conducting any analysis. Outliers were identified as data points outside of the 1.5 interquartile (IQR) range. There were no missing values.

Correlations

Bivariate correlations among all variables were computed. The correlations among the variables were low (all *r*s < 0.60). In line with Frederick (2005), Cokely and Kelley (2009) and Gómez-Chacón, García-Madruga, Vila, Elosúa, and Rodríguez, (2014) positive correlations were predicted between the measures of cognitive reflection and thinking (CRT, representativeness correct answers and belief bias syllogism accepted answers). Correlations among cognitive variables for the right DLPFC stimulation condition are presented in Table 5.2 and all correlations for the sham condition are presented in Table 5.3. For demographic variables see Table 5.1 in section 5.3.2.

Table 5.2. Correlations between all thinking task variables for the stimulation condition.

	Cognitive variables			
	1	**2**	**3**	**4**
1. CRT		-0.17	0.03	-0.10
2. Representativeness			0.05	0.04
3. Logic index				-0.34
4. Belief index				

Abbreviations: Cognitive Reflection Test (CRT). No correlates for cognitive variables were significant below $p < 0.05$.

Table 5.3. Correlations between all thinking task variables and demographics for the sham condition.

	Cognitive variables			
	1	**2**	**3**	**4**
1. CRT		-0.21	-0.08	0.12
2. Representativeness			-0.10	0.20
3. Logic index				-0.05
4. Belief index				

Abbreviations: Cognitive Reflection Test (CRT). No correlates for cognitive variables were significant below $p < 0.05$.

For all analyses that follow assumptions were checked during analysis including the distribution of the data. No assumptions were violated unless otherwise stated.

For the tasks tapping cognitive reflection performance (Cognitive Reflection Test and Representativeness) there was a maximum score of 3 items per task per session. A two-way repeated measures ANOVA was run with type of stimulation (right DLPFC or sham) and thinking task performance (Cognitive Reflection Test and Representativeness) as within-subjects variables.

There was a statistical main effect of stimulation on thinking task performance, F (1, 29) = 10.36, p = 0.01, partial $\eta^2 = 0.26$. Performance on the thinking tasks improved after the stimulation of the right DLPFC compared to sham (Figure 5.2).

There was also a statistically significant main effect of the type of task across stimulation conditions, $F(1, 29) = 6.91$ $p = 0.01$, partial $\eta^2 = 0.20$. CRT and representativeness performance with higher performance for the representativeness (stimulation: M = 2.00, SD = 1.11, sham: M = 1.43, SD = 1.13) compared to the CRT across stimulation conditions (stimulation: M = 1.30, SD = 0.87, sham: M = 0.86, SD = 0.90).

Follow-up t-tests showed that CRT performance was statistically higher in the right DLPFC stimulation condition (M = 1.30, SD = 0.87) than sham (M = 0.86, SD = 0.90) condition, $t(29) = 2.04$, $p = 0.051$. The second follow-up t-test revealed that representativeness vignette performance was higher in the right DLPFC stimulation condition (M = 2.00, SD = 1.11.) than sham (M = 1.43, SD = 1.13) condition, $t(29) = 2.54$, $p = 0.017$.

There was no 2-way interaction between stimulation condition and task, $F(1, 29) = 0.20$ $p = 0.66$, partial $\eta^2 = 0.01$.

An analysis was also run for logarithmic transformations on the performance scores.

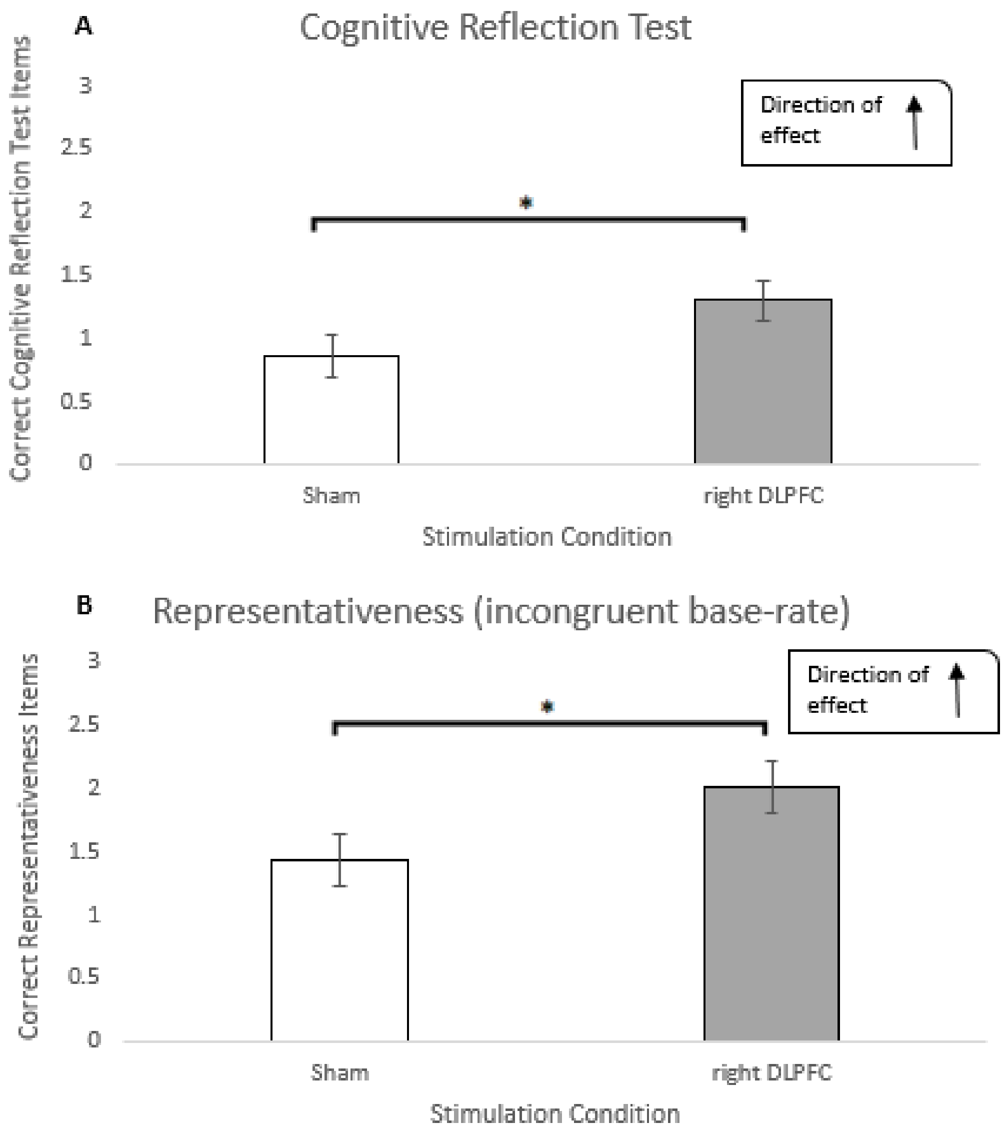


Figure 5.2. Effects of tDCS on thinking task performance. The panels show the effect of tDCS (sham or right DLPFC) on mean correct answers for the Cognitive Reflection Test (panel A) and mean correct answers for the representativeness (incongruent base-rate) (panel B). High values denote high levels of analytic thinking. Significance levels from follow-up t-tests, error bars denote standard errors from the mean: an asterisk denotes $p < 0.05$. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC).*

A second repeated measures ANOVA was run to examine the effects of stimulation on the logic index (maximum score of sixteen items per task in a session). Stimulation condition (right DLPFC or sham) was the within-subjects variable. There was no main effect of stimulation on the logic index, $F(1, 29) = 1.54$, $p = 0.22$, partial $\eta^2 = 0.05$.

The next repeated measures ANOVA examined the effects of stimulation on the belief index (maximum score of sixteen items per task in a session). Stimulation condition (right DLPFC or sham) was the within-subjects variable. There was no main effect of stimulation on the belief index, $F(1, 29) = 1.20$, $p = 0.30$, partial $\eta^2 = 0.04$.

For the intuitive incorrect answers in tasks tapping cognitive reflection performance (Cognitive Reflection Test and representativeness), a two-way repeated measures ANOVA was run with type of stimulation (right DLPFC or sham) and intuitive incorrect thinking task scores (Cognitive Reflection Test and representativeness) as within-subjects variables.

There was a significant main effect of stimulation on the number of intuitive answers, $F(1, 29) = 5.52$, $p = 0.02$, partial $\eta^2 = 0.16$. Intuitive responding decreased after stimulation of the right DLPFC compared to sham (Figure 5.3).There was no effect of the type of task across stimulation conditions, $F(1, 29) = 1.68$ $p = 0.20$, partial $\eta^2 = 0.05$.

The follow-up t-test for the intuitive CRT answers revealed that there was no difference between answers for the CRT after stimulation (M = 0.90, SD = 0.76), compared to sham (M = 1.13, SD = 0.90), $t(29) = -1.10$, $p = 0.30$.

The follow-up t-test for the intuitive representativeness sores found that there was a statistically significant difference between scores after stimulation compared to sham, $t(29) = -2.54$, $p = 0.017$. Intuitive responding decreased after the stimulation of the right DLPFC (M = 1.00, SD = 1.11) compared to sham (M = 1.56, SD = 1.13).

There was also no 2-way interaction between stimulation condition and intuitive task scores, $F(1, 29) = 1.50$ $p = 0.23$, partial $\eta^2 = 0.05$.

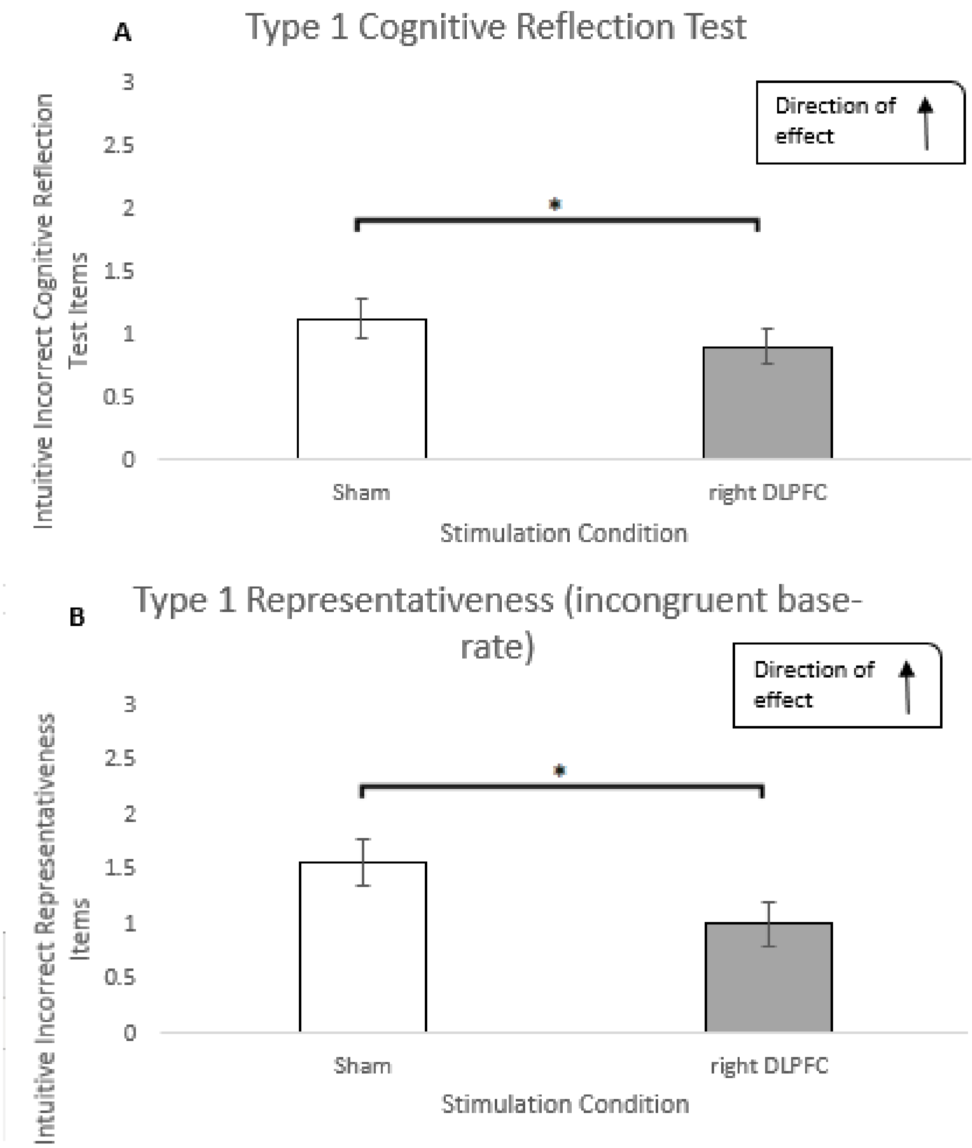


Figure 5.3. Effects of tDCS on intuitive incorrect thinking task performance. The panels show the effect of tDCS (sham or right DLPFC) on mean intuitive incorrect answers for the Cognitive Reflection Test (panel A) and mean intuitive incorrect answers for the representativeness (incongruent base-rate) (panel B). High values denote high levels of intuitive thinking. Significance levels from follow-up t-tests, error bars denote standard errors from the mean: an asterisk denotes $p < 0.05$. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC).*

Overall, the analyses showed that participants in the sham condition provided the fewest correct answers and that during anodal stimulation of the right DLPFC the number of correct answers increased compared to sham (Figure 5.4).

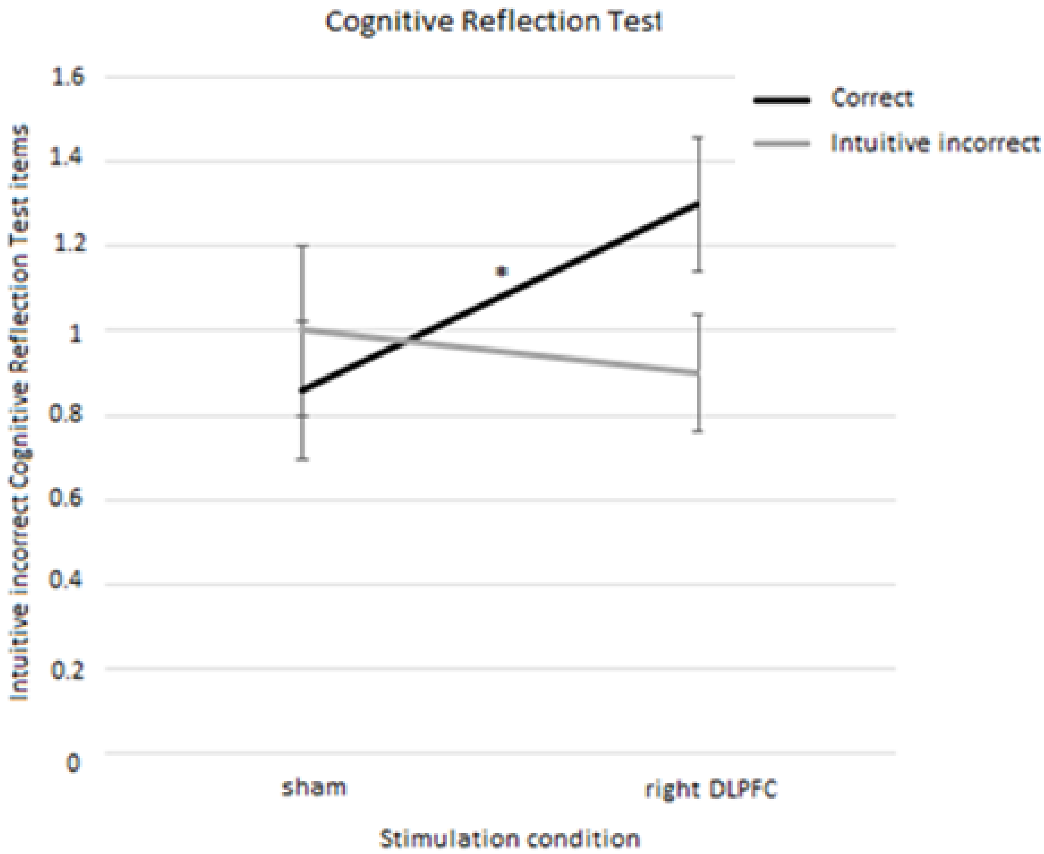


Figure 5.4. Effects of tDCS on Type 1 and Type 2 thinking task performance for the CRT. The effect of tDCS (sham or right DLPFC) on mean correct answers and mean intuitive incorrect answers for the Cognitive Reflection Test. High values for correct answers denote high levels of analytic thinking and high values for intuitive incorrect answers denote high levels of intuitive thinking. Significance levels from follow-up t-tests, error bars denote standard errors from the mean: an asterisk denotes $p < 0.05$. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC).*

The next repeated measures ANOVA examined the effect of stimulation (sham or right DLPFC) on risk-taking as measured by the Balloon Analogue Risk Task (BART).

There was no effect of stimulation on risk-taking performance, $F(1, 29) = 2.53$, $p = 0.12$, partial $\eta^2 = 0.08$.

The penultimate repeated measures ANOVA examined the effect of stimulation (sham or right DLPFC) on updating in the 2-back working memory task. There was no effect of stimulation on 2-back performance, $F(1, 29) = 0.17$, $p = 0.67$, partial $\eta^2 = 0.01$.

The final repeated measures ANOVA examined the effect of stimulation (sham or right DLPFC) on insight in the RAT. There was no effect of stimulation on RAT performance, $F(1, 29) = 0.74$, $p = 0.40$, partial $\eta^2 = 0.04$.

5.5 Discussion

This experiment showed that online anodal tDCS to the right DLPFC improved judgement and decision-making performance. The effect of stimulation was evident from the comparison with sham in which CRT and representativeness tasks improved suggesting improved Type 2 processing.

An important note here is that an increase in Type 2 processing is not necessarily the same as an increase in Type 1 processing – when using the CRT participants can respond in three ways: with a correct answer (Type 2), intuitive incorrect answer (Type 1) or an incorrect answer (neither Type 1 nor Type 2) (Frederick 2005; Toplak, West, and Stanovich 2011). If increasing Type 2 processing was the same as decreasing

Type 1 processing then there would be no third option when responding to CRT items. This emphasises the importance of these findings – that stimulation of the right DLPFC boosts Type 2 processing whilst not decreasing Type 1 processing here.

The main prediction was that online anodal tDCS of the right DLPFC would increase performance on judgement and decision-making tasks resulting in correct answers. This was based on the assumption for a role of the right DLPFC in executive functions that are associated with judgement and decision-making (Loftus et al., 2015; Santarnecchi et al., 2015). In particular, set-shifting (Tayeb & Lavidor, 2016), inhibition (Reteig et al., 2017) and working memory (updating) (Hill et al., 2016) - all crucial for the production of correct answers in the CRT and heuristics and biases battery (Evans, 2008; Toplak et al., 2011).

Importantly, there was no effect of stimulation of the right DLPFC on the belief bias syllogisms. A possible explanation for this is that unlike the CRT and heuristics and biases tasks our belief bias syllogisms did not require the inhibition of pre-potent responses (Frederick, 2005; Stupple et al., 2011; Thomson & Oppenheimer, 2016). To correctly answer a belief bias syllogism, one must assess the premises and the conclusion and decide whether a conclusion is acceptable or not (West et al., 2008; Toplak, West, & Stanovich, 2014).

Furthermore, there was no effect of online stimulation on risk-taking behaviour, as measured by the Balloon Analogue Risk Task (BART) (Lejuez et al., 2002) or insight in the RAT (Mednick, Mednick, & Mednick, 1964). The meta-analysis and systematic review in Chapter 4 found an effect of stimulation of the left frontal lobe, not the right DLPFC on risk-taking decision-making. At the time of commencing the first experiment the meta-analysis had not been completed so the right DLPFC was chosen as the site of stimulation because some of the papers included, found an effect of neuromodulation of the right DLPFC on risk-taking decision-making (Fecteau, Knoch, et al., 2007; Cheng & Lee, 2015).

It is possible that the stimulation only modulated decision-making that requires inhibitory control over pre-potent responses (e.g., as in the CRT), and not those that do not (e.g., as in the BART), as the right DLPFC is involved in inhibitory control (Santarnecchi et al., 2015). This increase in the cortical excitation in the right DLPFC therefore did not affect decision-making that is reliant on belief-based and logic-based reasoning (e.g., belief bias syllogisms), or risk-taking (e.g., BART) alone.

Limitations of this experiment were the bilateral tDCS montage in which the electrodes were positioned on contralateral hemispheres – the right DLPFC and left DLPFC. Some researchers may consider this a limitation and argue that any effect of stimulation was due to the decrease in excitability under the return electrode, and the increase in excitability at the site of the anode electrode. This bilateral montage was chosen for this experiment after the successful use of this montage in Hecht, Walsh, and Lavidor, (2013) and Minati, Campanhã, Critchley, & Boggio, (2012), in which this electrode arrangement reduced risk-taking decision-making. Experiment 2 examines this electrode montage further with the use of opposing (e.g., right DLPFC with left DLPFC, then left DLPFC with right DLPFC) stimulation parameters. The results of the bilateral right DLPFC and left DLPFC condition with sham. At the task level, a limitation was the small number of cognitive reflection task items that were available at the time of testing. When conducting this experiment there were a total of seven cognitive reflection test items available which were split into two sets of three for the two testing sessions. Since conducting this experiment more cognitive reflection test items have been published (Thomson & Oppenheimer, 2016).

5.6 Summary

This experiment is the first experimental evidence of the involvement of the right DLPFC in judgement and decision-making tasks. Online stimulation of the right DLPFC boosted Type 2 processing resulting in improved correct answers for the cognitive reflection test and representativeness tasks.

In the next chapter (Chapter 6) experiment 2 builds on the results from the first experiment (this chapter). The next chapter does this by firstly, increasing the number of CRT items from six to twenty, secondly by including CRT items that both rely on, and do not rely on numeracy skill, and finally, by using offline neuromodulation only – as opposed to both online and offline stimulation in this chapter.

Chapter 6

The effect of tDCS modulation on cognitive reflection and thinking disposition in Stanovich's tripartite model (2009)

6.1 Background

The results of Experiment 1 revealed that the right DLPFC is involved in Type 2 decision-making such as cognitive reflection (Chapter 5). Anodal neuromodulation of the right DLPFC significantly improved performance in the CRT and representativeness vignettes. There was no change to executive functioning, as measured by the n-back, after stimulation. Experiment 2 examines the neural correlates of the dual-process framework of judgement and decision-making by building on Experiment 1 with an expanded battery of decision-making tasks (the CRT, verbal CRT, belief bias syllogisms and representativeness vignettes) and additional executive function tasks (the n-back with levels of 2 and 3, plus the Attention Switching Task). These tasks are all involved in crucial components of dual-process framework, in particular Stanovich's tripartite model (Stanovich, 2009).

As discussed in Chapter 3 (see section 2.1.4.3 – Stanovich's tripartite model), some of the variance in CRT performance was explained by thinking dispositions (Stanovich, 2009; Toplak, West, & Stanovich, 2011; Baron, Scott, Fincher, & Metz, 2015) and cognitive ability (Nelson and Willison 1991). Thinking dispositions are the tendency towards patterns of thinking that are based on individual differences (Ennis, 1962), whilst cognitive ability (i.e., intelligence) is the ability to acquire and manipulate new information. For example, actively open-minded thinking (AOT) represents the willingness to change one's mind after assimilating new information which conflicts with a previously held view. Individuals who score highly on the AOT scale (Baron et al., 2015) are thus open-minded to new information, and high AOT scores have been positively correlated with performance in the CRT and belief bias syllogistic reasoning (Campitelli & Labollita, 2010). This experiment accounted for potential relationships with thinking disposition, using the AOT scale (Baron, 1985) and Rational Experiential Inventory (REI) (Epstein, Pacini, Denes-Raj, & Heier, 1996). Like the AOT, the REI is a thinking disposition that positively correlates with tasks such as the CRT that measure cognitive reflection (Liberali et al. 2012). Cognitive ability was examined using the National Adult Reading Test (Crawford, Parker, Stewart, Besson, & Lacey, 1989; Nelson & Willison, 1991). These thinking dispositions and the cognitive ability measure (NART) are used as cognitive characteristics in this experiment to examine whether there are any a priori differences between experimental groups – to the best of my knowledge this is the first stimulation experiment to control for individual differences (now published as Edgcumbe et al., 2019). By controlling for these cognitive characteristics there can be certainty about the source of any effects of stimulation on cognitive reflection – if there is no difference between experimental groups for cognitive characteristics than the change in cognitive reflection can only be explained by the stimulation (as opposed to cognitive characteristics).

This experiment is motivated by Stanovich's (2009) tripartite model of decision-making. Crucially, this model divides Type 2 thinking between the reflective mind (i.e. where thinking dispositions reside) and the algorithmic mind (i.e., the source cognitive ability). The separation of Type 2 thinking into these minds therefore enables the relationship between the properties of these minds (thinking disposition or cognitive ability) to be assessed with cognitive reflection. From this model one can predict that when two individuals with the same level of cognitive ability (the algorithmic mind) answer CRT questions, differences in their Type 2 performance can be explained by differences in thinking disposition (the reflective mind). Between these two individuals, low performance on the AOT thinking disposition, causes the reflective mind to override the algorithmic mind, resulting in an incorrect answer to the CRT. The second person with high inclination to reflective thinking would be more likely to answer the CRT correctly. At the lower level of this model Type 1 thinking is as in other dual-process models with no separation of this process (see section 3.1.4.3) (Evans 2006; Pennycook, Fugelsang, and Koehler 2015).

In the only other experiment to combine tDCS and the CRT, other than those contained in this thesis (at the time of running Experiment 2), Oldrati, Patricelli, Colombo, and Antonietti, (2016) applied cathodal tDCS to the left DLPFC (with a contralateral return electrode). They reported that cathodal stimulation of the left DLPFC was associated with an increase in Type 1 thinking, as measured by incorrect intuitive answers on the CRT. To build on the work of Oldrati et al., Experiment 2 included a left DLPFC stimulation group in which anodal stimulation was applied to this region. In line with the findings of Oldrati one would predict that Type 1 thinking should decrease after the stimulation of the left DLPFC.

A further addition to Experiment 2 which builds on the findings of Experiment 1 is to investigate any differences in numeracy-based cognitive reflection (Frederick, 2005; Toplak et al., 2011) and cognitive reflection without numeracy (Thomson &

Oppenheimer, 2016; Sirota, Kostovicova, Juanchich, Marshall, & Dewberry, 2017). The reason for including numeracy-based and none-numeracy based CRT items is that some theorists suggest that performance on the CRT can be explained by numeracy ability alone (Liberali et al. 2012; Sinayev and Peters 2015), for example, those who score highly on tests of numeracy also score highly on the CRT. This line of reasoning is supported by the positive correlations between numeracy and CRT performance that are reported in many studies (Cokely and Kelley 2009; Thomson and Oppenheimer 2016). The original version of the CRT (hereafter called the CRT) that was published by Frederick (2005) and then built on by Toplak et al., (2011) solely contains CRT items in which mathematical ability is needed to correctly respond with the Type 2 solution. Several CRT items that do not require numeracy / mathematics to complete have since been created (hereafter called the verbal CRT) (Sirota et al., 2017). This experiment includes both versions of the CRT so that the effects of stimulation on the right DLPFC can be examined with either version of the CRT. By including both versions of the CRT, the involvement of numeracy in CRT performance was examined.

In order to investigate the involvement of executive functions in the dual-process framework of judgement and decision-making inhibition and updating tasks were included in this experiment. As in Experiment 1 (Chapter 5) the n-back was used to examine updating (Jaeggi et al. 2010) whilst the Attention Switching Task (AST) was used to assess inhibition (Hanania and Smith 2010). One explanation for not finding an effect of stimulation of the right DLPFC on the 2-back in Experiment 1 was that participants found the task to be too easy, and a ceiling effect pattern was supported by the high performance on this task. A harder version of the n-back, with a level of 3 (i.e., the 3-back) was therefore used alongside the 2-back in this experiment. As updating (n-back) and inhibition (AST) are both critical executive functions that underpin the dual-process framework it was predicted that as Type 2 thinking performance increases so does inhibition and updating.

In a between-subjects design, decision-making performance was measured following offline anodal tDCS applied bilaterally to either the left DLPFC, right DLPFC or a sham stimulation. The reasons for the change from online (Experiment 1) to offline stimulation (Experiment 2) was twofold: (i) Oldtrati et al., (2016) used offline stimulation so the efficacy of this form of neuromodulation was examined here, and (ii) offline stimulation increases the data collection duration from twenty minutes to forty minutes. With the increased data collection duration, more tasks (e.g., the AST) could be administered to achieve the aims of this experiment, compared to Experiment 1 (Chapter 5). It was hypothesised that anodal tDCS to the right DLPFC would inhibit Type 1 processing, thus increasing cognitive reflection scores and reducing heuristic thinking. In contrast, syllogistic reasoning (as measured by the logic index) would be affected by stimulation of the left DLPFC rather than the right DLPFC as this type of reasoning has been associated with left frontal activation (Goel et al. 2009; Luo et al. 2014), performance here does not rely on the inhibition of pre-potent Type 1 thinking (Luo et al. 2014). Crucially, the prediction was that if Type 1 processing is dissociable from Type 2 processing, then only anodal stimulation to the right DLPFC would improve Type 2 performance.

6.2 Research questions

It was asked whether the intuitive thinking (Type 1), cognitive reflection (Type 2), inhibition (Attention Switching Task), and working memory (2-back & 3-back) are modified by anodal tDCS of the right dorsolateral prefrontal cortex (right DLPFC) and / or the left DLPFC. Furthermore, the aforementioned processes are discussed with reference to Stanovich's tripartite model (2009).

Research question 1

Does offline anodal tDCS of the right DLPFC enhance cognitive reflection as measured by the Cognitive Reflection Test (CRT) and representativeness (incongruent base-rate) vignettes?

Prediction 1: offline anodal stimulation of the right DLPFC will increase Type 2 responses as shown by higher accuracy scores for the enhanced CRT and representativeness vignettes after stimulation compared to sham.

Research question 2

Does offline anodal tDCS of the right DLPFC enhance cognitive reflection in the verbal CRT?

Prediction 2: offline anodal stimulation of the right DLPFC will increase cognitive reflection that does not rely on numeracy as shown by higher accuracy scores after stimulation for the verbal-CRT compared to sham.

Research question 3

Does offline anodal tDCS of the right DLPFC or left DLPFC moderate decision-making that has no cognitive reflection (e.g., syllogistic reasoning)?

Prediction 3: offline anodal stimulation of the right DLPFC will increase decision-making that does not rely on cognitive reflection as shown by higher accuracy scores for syllogistic reasoning after stimulation compared to sham.

Research question 4

Does offline anodal tDCS of the left DLPFC enhance or inhibit cognitive reflection as measured by the CRT, verbal-CRT and / or representativeness (incongruent base-rate) vignettes?

Prediction 4: offline anodal stimulation of the left DLPFC will increase cognitive reflection as shown by higher accuracy for the CRT, verbal-CRT and representativeness vignettes after stimulation compared to sham.

Research question 5

Does offline anodal tDCS of the right DLPFC or left DLPFC affect working memory (updating) as measured by the 2-back and 3-back?

Prediction 5: offline anodal stimulation of the right and left DLPFCs will increase working memory performance as shown by higher accuracy after stimulation for the 2-back and 3-back compared to sham.

Research question 6

Does offline anodal tDCS of the right DLPFC or left DLPFC affect the inhibition of pre-potent responses in the Attention Switching Task?

Prediction 6: offline anodal stimulation of the right and left DLPFCs will increase inhibitory performance as shown by higher accuracy in the Attention Switching Task after stimulation compared to sham.

6.3 Methodology

6.3.1 Design

This experiment adopted a between-subjects design. The independent between-subjects variable was stimulation group (anodal right DLPFC, anodal left DLPFC or sham). Stimulation began before the start of the behavioural tasks and continued whilst the participants relaxed in a comfortable chair. The tDCS equipment was removed from the participant's head after twenty minutes of stimulation after which participants began the tasks (known as 'offline' stimulation) (Figure 6.1). Unlike Experiment 1 offline stimulation was used here rather than online stimulation because (i) this type of neuromodulation allows for data collection that exceeds twenty minutes in duration, and (ii) the effects of offline stimulation of the left DLPFC on cognitive reflection had been revealed by Oldrati et al., (2016).

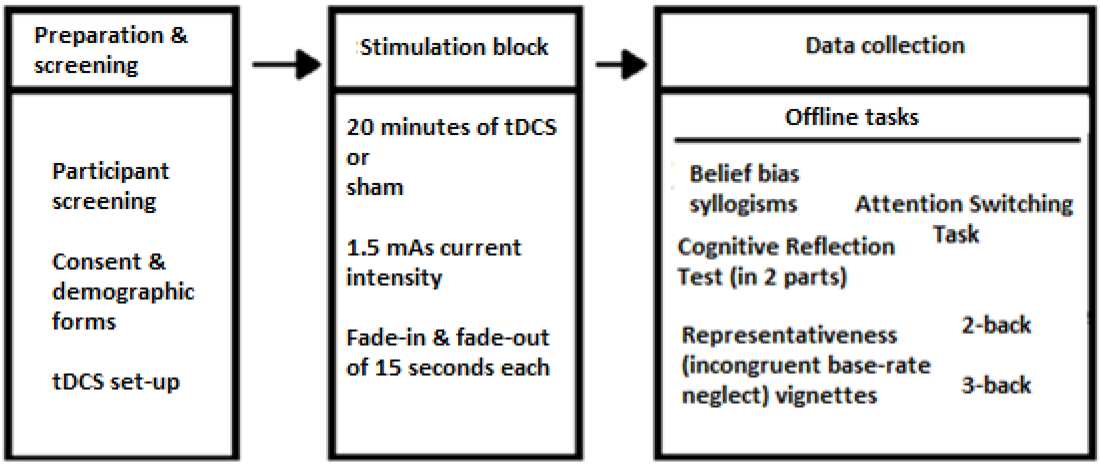


Figure 6.1. An overview of the procedure used in Experiment 2. Arrows denote time course. The Cognitive Reflection Test, Representativeness (incongruent base-rate neglect) vignettes, belief bias syllogisms, attention switching, 2-back and 3-back were administered to participants after twenty minutes of stimulation (offline). All tasks were counterbalanced during data collection.

6.3.2 Participants

Fifty-four participants were recruited through advertising (e.g., online websites, and posters on campus) and word-of-mouth at The University of East London (UEL) (mean age = 24.63 ± 4.46 years; 29 females).

A power analysis calculation using G Power 3.0 revealed that a sample size of 33 participants was needed to reach a significant result. This was based on a medium effect size of f = 0.30, according to the convention set out by Cohen (1969, p348), and an alpha (α) significance level of p = 0.05 in a between-subjects design experiment with a total of 6 measures and 3 groups.

The inclusion criteria were (i) aged 18 years or above; (ii) fluent English speakers; (iii) right-handed; (iv) naïve to tDCS and (v) naïve to the behavioural tasks used. The exclusion criteria were (i) history of seizures; (ii) family history of seizures; (iii) past or present neurological history; (iv) past or present psychiatric history; (v) past head injury or surgery; (vi) metal implants; (vii) current medication usage; (viii) drug or alcohol dependence; (ix) pregnancy and (x) past training in logic reasoning (e.g., during a university course). All participants provided informed written consent. The experiment was approved by The University of East London (UEL) Research Ethics Committee. After giving consent participants completed all scales and questionnaires (NART, AOT and REI), and the demographic form containing information about sex (male, female or do not wish to say), age, religiosity (1 = not at all religious to 5 = very religious), paranormal beliefs (yes or no) and education level – self reported highest current education level (Table 6.1). Participants were asked about religiosity based on the dual-process framework literature that suggest that high levels of religiosity positively correlates with high levels of intuitive thinking on the CRT (Pennycook et al., 2012; Razmyar & Reeve, 2013).

Table 6.1. Demographics and cognitive characteristics

	Stimulation group mean (SD)		
Demographic variable	**Left DLPFC**	**Sham**	**Right DLPFC**
Sex (F/M)	9/9	9/9	11/7
Age (years)	23.78 (4.63)	24.83 (4.60)	25.28 (4.26)
Religious (Yes/No)	10/8	10/8	9/9
Education	5.80 (1.06)	6.30 (1.07)	6.67 (0.70)
Cognitive characteristics			
NART score	117.83 (4.80)	117.90 (5.91)	118.61 (4.60)
AOT score	38.67 (7.17)	40.83 (3.11)	39.06 (3.45)
REI 10 R subscale	16.83 (3.10)	19.44 (2.72)	18.22 (3.37)
REI 10 E subscale	15.22 (1.86)	15.67 (1.57)	16.17 (1.46)

Education represents the qualification level. Abbreviations: Standard Deviations (SD), Dorsolateral prefrontal cortex (DLPFC), females (F), males (M), National Adult Reading Test (NART), Actively open-minded thinking (AOT), Rational Experiential Inventory Rational subscale (REI 10 R), Rational Experiential Inventory Experiential subscale (REI 10 E).

6.3.3 tDCS montage and parameters

As in Experiment 1 the same tDCS device, electrode sizes, sham procedure and current intensity (1.5mA) were used. TDCS was delivered using a battery-driven stimulator device (Neuroelectrics, Barcelona) using two sponge electrodes (anodal and return) each circular with a surface area of 25cm^2. In the stimulation groups, a constant current was administered for 20 minutes before testing ('offline'). The tDCS montage was dependent upon the stimulation group (anode electrode – return electrode): (i) anode right DLPFC return left DLPFC, (ii) anode left DLPFC return right DLPFC or (iii) sham right DLPFC sham left DLPFC condition. The electrodes were placed over the right DLPFC (F4) or left DLPFC (F3) according to the EEG 10-20 international system (Herwig, Satrapi, & Schönfeldt-Lecuona, 2003). The ramp-up and ramp-down time were 15 seconds each at the onset and offset of stimulation to decrease the likelihood of discomfort. The sham group consisted of 15 seconds of stimulation at the beginning and end of the 20 minutes.

6.3.4 Materials and measures

All materials used in this experiment were validated and established tasks from the literature. Furthermore, all tasks were counterbalanced to guard against carry-over effects and other confounds (Figure 6.1). The Cognitive Reflection Test (Oldrati et al., 2016), n-back (Hill, Fitzgerald, & Hoy, 2016) and belief bias syllogisms (Tsujii, Sakatani, Masuda, Akiyama, & Watanabe, 2011) have been used in previous neuromodulation studies. See Appendix B for all items contained within this experiment.

Cognitive Reflection Test and verbal-CRT: As described in Chapter 4 the Cognitive Reflection Test (CRT and verbal-CRT) was administered in this experiment in two parts of equal numbers of items. The CRT used in Experiment 2 consisted of a total of twenty CRT items (the CRT plus the verbal-CRT) which were administered to participants in two parts of ten items. For the original, numeracy-based CRT (called the CRT throughout this thesis) there were eight items with a maximum score of eight. For the verbal-CRT there were twelve items with a maximum score of twelve. Participants had a maximum of twenty minutes to answer all CRT and verbal-CRT items. The use of the verbal-CRT in this experiment is the first time that this task has been paired with tDC stimulation. The verbal-CRT has been validated in previous non-stimulation experiments (Sirota, 2017). In the example of a verbal-CRT item below the incorrect intuitive Type 1 answer is the monkey or bird, whilst the correct Type 2 answer is that there are no bananas in coconut trees.

A monkey, a squirrel, and a bird are racing to the top of a coconut tree. Who will get the banana first, the monkey, the squirrel, or the bird?

The CRT and verbal-CRT have the same item structure, participants respond with free choices in both tasks and the tasks only differ in their reliance on numeracy.

Other tasks used in previous chapters: As described in Chapter 5 the n-back, belief bias syllogisms and representativeness vignettes (also called incongruent base-rate vignettes) were used in this experiment. The n-back contained a total of one hundred and twenty trials (correct and incorrect) were presented to participants for a maximum score of thirty. Belief bias syllogisms consisted of a total of sixteen items with 4 valid-unbelievable, 4 valid-believable, 4 invalid-unbelievable and 4 invalid-believable items. There was a total of ten representativeness vignettes with a maximum score of ten. The following additional tests were used in Experiment 2:

Attention Switching Task: The attention switching task (AST) is a measure of inhibition (Hanania & Smith, 2010). Participants see an arrow that points either to the right or to the left with an instruction above the arrow indicating to report either (i) the direction that the arrow is pointing in (right or left) or (ii) the side of the screen that the arrow is on (right or left).

A total of one hundred and twenty trials (sixty congruent and sixty incongruent) were administered to participants. Participants took a maximum of five minutes to complete the AST.

Actively Open-minded Thinking: The actively open-minded thinking (AOT) scale measures the willingness to consider new information and remain ‘open-minded’ (Stanovich & West, 1997; Haran, Ritov, & Mellers, 2013). The short-form version of the AOT was administered in this experiment with a total of seven items. Participants took a maximum of five minutes to complete this task and responded on a scale from 1 (completely disagree) to 7 (completely agree).

Rational Experiential Inventory: The rational experiential inventory (REI) measures cognitive style (the use of intuitive or analytic thinking) (Epstein et al., 1996). The short form of the REI was administered in this experiment with a total of ten items. Participants took a maximum of five minutes to complete this task and responded on a scale from 1 (strongly disagree) to 5 (strongly agree).

National Adult Reading Test: The National Adult Reading Test (NART) is a list of 50 short words with irregular pronunciation (e.g., BOUQUET, PLACEBO) (Crawford et al., 1989; Nelson & Willison, 1991). Performance on the NART predicts cognitive ability (i.e., intelligence) in the Weschler Adult Intelligence Scale (WAIS) (Crawford et al., 1989). Participants are scored on their pronunciation of words in the test which takes a maximum of five minutes to complete.

6.4 Analysis Plan

The raw data were screened for outliers and missing values before conducting any analysis. Outliers were identified as data points outside of a 1.5 interquartile (IQR) range. There were no missing values.

A first analysis investigated whether there were any *a priori* differences between groups regarding thinking styles as this could potentially explain stimulation results. A multivariate analyses of variance (MANOVA) was performed, with type of stimulation (right DLPFC, left DLPFC or sham) as the between-subject factor. Dependent variables were the REI subscales: rationale (REI 10 R) and experiential (REI 10 E), the actively open-minded thinking scale (AOT) and National Adult Reading Test (NART).

6.4.1 Judgement and decision-making analyses

To test the effects of stimulation on Type 2 responses, a further multivariate analysis of variance (MANOVA) was performed with type of stimulation (right DLPFC, left DLPFC or sham) as the between-subject factor. Dependent variables were correct answers for the CRT, correct answers for the verbal-CRT, the number of correct answers from the representativeness questions, and the Logic Index from the belief bias syllogisms. Significant effects were analysed with ANOVAs to determine the specific contributing contrast.

To examine the effect of stimulation on the belief index (from the belief bias syllogisms) a separate analysis of variance was performed with the type of stimulation (right DLPFC, left DLPFC or sham) as the between-subject factor. The dependent variable was the belief index score.

To test intuitive incorrect answers (Type 1), a third multivariate analysis of variance (MANOVA) was conducted with the type of stimulation (right DLPFC, left DLPFC or sham) as the between-subject factor. Dependent variables were all intuitive incorrect answers for the CRT, verbal-CRT, and the representativeness vignettes.

6.4.2 Executive functioning: working memory (updating) task analysis

The next multivariate analysis of variance (MANOVA) examined the effect of stimulation on working memory (updating). The between-subject factor was type of stimulation (right DLPFC, left DLPFC or sham). Dependent variables were number of correct 2-back answers and correct 3-back answers.

6.4.3 Executive functioning: inhibition task analysis

The final analysis of variance (ANOVA) then examined the effect of stimulation on inhibition. Between-subject factor was Attention Switching Task (AST) effect score (correct congruent answers minus correct incongruent answers).

6.5 Results

There were no missing values or outliers in the correct mean scores for the thinking tasks (i.e., CRT, representativeness and belief bias syllogisms), nor were there any missing values for the cognitive characteristics. Table 6.2 shows the relevant summary for means and standard deviations for all thinking tasks with stimulation group. The assumptions of each analysis were examined at analysis. Unless otherwise stated there were no violations of assumptions.

Table 6.2. Raw data for the battery of thinking tasks (mean sum total across participants in group and standard deviations). Reflective / correct answers are provided for the Cognitive Reflection Test (CRT: for the CRT there were 8 items; verbal-CRT 12 items) and the representativeness (incongruent base-rate) problems (10 items). Belief bias syllogism variables were the Logic index and belief index – these were calculated from a total of 16 items.

	Stimulation group		
Task / measure	**Left DLPFC**	**Sham**	**Right DLPFC**
CRT correct	3.33 (2.14)	3.72 (1.67)	5.33 (2.50)
Verbal-CRT correct	4.11 (2.74)	3.11 (2.11)	4.05 (2.20)
Representativeness correct	4.33 (3.51)	4.22 (2.82)	6.83 (4.06)
BBS Logic Index	0.33 (1.80)	1.94 (2.12)	1.88 (2.24)
BBS Belief Index	-2.77 (1.63)	-3.38 (1.24)	-3.11 (1.60)

Abbreviations: Dorsolateral prefrontal cortex (DLPFC), Cognitive Reflection Test (CRT), Belief bias syllogisms (BBS).

A MANOVA with cognitive characteristics as dependent variables showed no effect of stimulation group (Pillai's trace = 0.18, p = 0.28) on thinking disposition. The Box's test results showed that equality of covariance had been violated (p = 0.03) so Pillai's trace was used. Thus, the three experimental groups did not differ in the cognitive characteristics scores (see Table 6.1), which have previously been associated with judgement and decision-making performance (e.g., Toplak et al., 2011).

The second MANOVA tested the effect of stimulation on the judgement and decision-making performance. The Box's test results showed equality of covariance matrices,

p = 0.946. There was a significant main effect of stimulation, Wilks' λ = 0.67, F(8, 96) = 2.602.63, p = 0.01, partial η^2 = 0.17, on thinking task performance – showing that performance improved after stimulation compared to sham.

Follow-up ANOVAs revealed that there were main effects of stimulation group on CRT scores, F(2, 51) = 4.45, p = 0.01, partial η^2 = 0.15, representativeness correct answers, F(2, 51) = 3.20, p = 0.04, partial η^2 = 0.11, and the Logic Index, F(2, 51) = 3.54, p = 0.03, partial η^2 = 0.12. Performance increased following right DLPFC anodal stimulation compared to sham for the CRT scores and representativeness answers. For the Logic Index, scores were higher for the right DLPFC stimulation compared to left DLPFC stimulation only. There was no effect of stimulation group on verbal-CRT, F(2, 51) = 1.02, p = 0.37, partial η^2 = 0.04, scores. The relevant summary for means and standard deviations for both stimulation groups are presented in Figure 6.2.

Planned contrasts revealed that CRT performance improved following right DLPFC anodal stimulation (M = 5.33, SD = 2.50) in comparison to both left DLPFC anodal stimulation, F(2, 51) = 4.45, p = 0.01, 95% CI [-3.42, -0.57] (M = 3.33, SD = 2.14) and sham, F(2, 51) = 4.45, p = 0.03, 95% CI [-3.03, -0.20] (M = 3.72, SD = 1.67).

The planned contrasts revealed that representativeness performance was higher following right DLPFC anodal stimulation (M = 6.83, SD = 4.06) in comparison to both left DLPFC anodal stimulation, F(2, 51) = 3.20, p = 0.03, 95% CI [-4.84, -0.15] (M = 4.33, SD = 3.51) and sham, F(2, 51) = 3.20, p = 0.03, 95% CI [-4.95, -0.26] (M = 4.22, SD = 2.82).

For the logic index, planned contrasts revealed that logical responding was higher following right DLPFC anodal stimulation (M = 1.88, SD = 2.24) in comparison to left DLPFC anodal stimulation, $F(2, 51) = 3.54$, $p = 0.03$, 95% CI [-2.93, -0.17] (M = 0.33, SD = 1.80), but not to sham, $F(2, 51) = 3.54$, $p = 0.93$, 95% CI [-1.32, 1.43] (M = 1.94, SD = 2.12).

A post-hoc t-test examined the effect of stimulation of the left DLPFC versus sham for the Logic Index. The t-test revealed a difference between Logic Index performance after left DLPFC stimulation compared to sham, $t(34) = 2.46$, $p = 0.02$, 95% CI [0.28, 2.94] – performance was worse after left DLPFC stimulation (M = 0.33, SD = 1.78) compared to sham (M = 1.94, SD = 2.12).

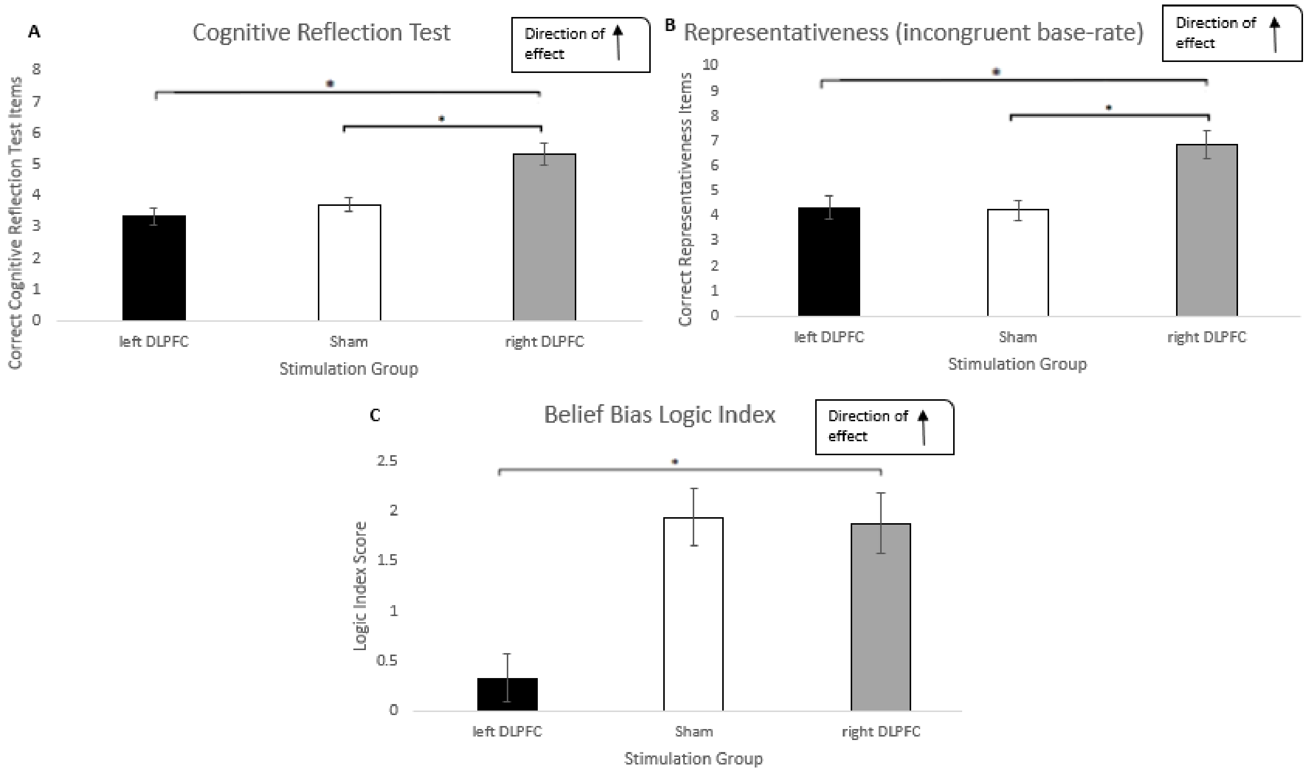


Figure 6.2. Effects of tDCS neuromodulation on thinking task performance. The panels show the effects of tDCS (left DLPFC, sham, or right DLPFC) on mean correct answers for the Cognitive Reflection Test (panel A), mean correct answers for representativeness (incongruent base-rate neglect) vignettes (panel B), and the effects of tDCS on the Logic Index for the belief bias syllogisms (panel C). Comparisons were right DLPFC vs. sham, and right DLPFC vs. left DLPFC. High values for all panels denote high levels of analytic thinking. Significance levels from planned contrasts in follow-up analysis of variance (ANOVAs), error bars denote standard errors from mean: an asterisk denotes p < 0.05. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC), Cognitive Reflection Test (CRT).*

Next, a separate analysis of variance (ANOVA) examined the effect of stimulation on the belief index. There was no effect of simulation on the belief index, $F(2, 51) = 0.74$, $p = 0.48$, partial $\eta^2 = 0.03$.

The third MANOVA tested the effect of stimulation on the judgement and decision-making tasks for Type 1 intuitive thinking answers. The Box's test results showed equality of covariance matrices (p = 0.98). There was no main effect of stimulation, Wilks' λ = 0.82, $F(6, 98) = 1.65$, p = 0.14, partial $\eta^2 = 0.10$ on intuitive response scores.

The next multivariate analyses of variance (MANOVA) was performed to examine the effects of stimulation on updating (2-back and 3-back). The independent variable was the type of stimulation (right DLPFC, left DLPFC or sham). Dependent variables were number of correct 2-back answers and correct 3-back answers. The Box's test of equality of covariance matrices was supported, p = 0.21. There were no multivariate effects using Wilks' Lambda for the factors of stimulation, Wilks' λ = 0.88, $F(4, 100)$ = 1.53, p = 0.20, partial $\eta^2 = 0.06$. There were no main effects for the factor of stimulation on 2-back correct answers, $F(2, 51) = 0.45$, p = 0.64, partial $\eta^2 = 0.02$ or 3-back correct answers, $F(2, 51) = 1.2$, p = 0.29, partial $\eta^2 = 0.05$.

To examine the effect of stimulation on inhibition in the AST a one-way analyses of variance (ANOVA) was performed. Dependent variable was AST effect (correct congruent answers minus correct incongruent answers) and between-subject factor was stimulation (right DLPFC left DLPFC or sham). There was no effect of stimulation on AST effect, $F(2, 51) = 0.76$, p = 0.47, partial $\eta^2 = 0.03$.

6.6 Discussion

Experiment 2 showed that, as compared to sham, offline anodal tDCS over the right DLPFC (with return electrode over left DLPFC) improves the number of correct answers on the Cognitive Reflection Test (Toplak et al., 2011; Thomson & Oppenheimer, 2016) and representativeness heuristics. In contrast, logical thinking was impaired when the left DLPFC was bilaterally stimulated (compared to right DLPFC). These results reflect those of Experiment 1 (albeit using online stimulation) that when applied to the right DLPFC anodal stimulation increases judgement and decision-making performance. The results also extend previous work by Oldrati et al., (2016), who showed a decrease in CRT performance after unilateral cathodal stimulation compared to anodal stimulation. To the best of our knowledge this is the first evidence (with Experiment 1) of an improvement in cognitive reflection from the application of an offline direct current to the right DLPFC.

The main predictions were that increasing cortical excitability of the right DLPFC would increase performance on judgement and thinking tasks that require inhibition of automatic processes in order to result in normatively correct (unbiased) answers. This was based on the concept of an algorithmic mind (Stanovich, 2009; Stanovich, West, & Toplak, 2013) monitoring and inhibiting (Type 1) processes from an autonomous mind. TDCS over the right DLPFC is known to affect executive functions (Del Missier, Mäntylä, & Bruine de Bruin, 2010; Del Missier, Mäntylä, & Bruin, 2012) that include impulsivity control and set-shifting (Loftus et al., 2015). Greater resistance to intuitive thinking and pre-potent CRT responses rely on the engagement of impulsivity control and set-shifting during decision-making (Del Missier et al., 2012). The findings that stimulation of the right DLPFC did improve cognitive reflection performance for mathematical CRT items and representativeness therefore is a direct test of the existence of a neural correlate for Type 2 cognitive reflection. In addition, this study showed that thinking tasks that arguably rely less on inhibition (syllogisms) and that did not include any belief bias components (using the logic index only) showed no improvement between right stimulation and sham, but did show an impairment after left DLPC stimulation (Stupple, Ball, Evans, & Kamal-Smith, 2011; Stupple et al., 2013). Previous brain imaging studies (Goel, Buchel, Frith, & Dolan, 2000; Goel & Dolan, 2003), showed a relationship between the neural correlates of inhibition and Type 2 (reflective thinking) processes. Importantly, this study went further than previous comparable work (e.g., Oldrati et al., 2016) by controlling for individual differences with the NART, AOT, and REI – differences that presumably can influence decision-making (Stanovich & West, 1997; Campitelli & Labollita, 2010).

However, if increased performance in the CRT and Representative vignettes were the result of inhibition processes, then we would have expected that Type 1 (intuitive) scores (in the additional analyses) would show a reduction. Similar to the results (for the CRT at least) in Experiment 1, however, there was no reduction in intuitive answers, so no indication of inhibition of prepotent associative answers after stimulation.

For belief bias syllogisms (using the belief index) there was no effect of direct current stimulation. There are at least two reasons why an increase of cortical excitability of the right DLPFC might not influence syllogistic reasoning (logic index score). Firstly, the dual-process theories of decision-making do not postulate that reasoning based on belief needs to be inhibited for all task variants. In some instances, beliefs are correct when logic and beliefs do not conflict, for example in no-conflict syllogisms (Ball, Phillips, Wade, & Quayle, 2006; De Neys & Schaeken, 2007). Here cognitive reflection and inhibitory control are not needed. Secondly, direct current stimulation was applied to the DLPFC - a brain region that is associated with executive functions (Loftus et al., 2015) that are needed for correctly responding to conflict, but not for no-conflict belief-bias syllogisms. Rather than the DLPFC, the inferior frontal cortex (IFC) is associated with correctly solving no-conflict syllogisms (De Neys & Glumicic, 2008; Tsujii, Sakatani, Masuda, Akiyama, & Watanabe, 2011). Left DLPFC stimulation (compared to right-DLPFC stimulation) did in fact reduce performance on the logic index – an area of the brain that is associated with self-regulation (Mengarelli et al., 2015), affective modulation (Hare et al., 2009) and attentional processing (Goel et al., 2006).

As the dual-process framework of decision-making posits that executive functions (i.e., inhibition, updating) are crucial components of this framework (Sloman 1996; Evans and Stanovich 2013) it was hypothesised that any change in cognitive reflection would be mirrored by a change in these executive functions. There was no significant effect of anodal stimulation on inhibition or updating. For updating, in which the 2-back and 3-back were administered this is explained by the ease of the 2-back and difficulty of the 3-back (Jaeggi et al. 2010; Hill, Fitzgerald, and Hoy 2016). The results of the 2-back suggested that across all stimulation groups participants performed at ceiling, scoring an almost perfect score of thirty out of thirty trials correct. Conversely, participants found that the 3-back was too difficult so scored poorly across all stimulation groups. To remedy this problem Experiment 3 uses an additional validated working memory (updating) task, the Sternberg task (Sternberg 1969).

As for inhibition the AST task was administered (Hanania and Smith 2010). There are two explanations for not finding an effect of stimulation on the AST. Firstly, the results revealed that across all stimulation groups participants scored highly on this task, suggesting that they found this task to be too easy. Secondly, the AST is thought to measure a form of planned inhibition (called 'far inhibition') rather than a singular type of inhibition (Hanania and Smith 2010). During planned inhibition participants see the instruction prior to viewing the stimuli, thus giving them time to anticipate and prepare a response (Hanania and Smith 2010). If the planned inhibition is not the same type of inhibition that is involved when Type 2 thinking override the pre-potent Type 1 response then no change in planned inhibition would be expected. In Experiment 3 the Stop-Signal Task (Boehler et al. 2010), which is thought to not reply on planned inhibition was administered.

Critics of the CRT make the claim that the CRT is a test of numerical ability rather than cognitive reflection (Weller et al., 2013; Welsh, Burns, & Delfabbro, 2013). Indeed, there was an effect of bilateral right DLPFC stimulation for the typical (numerical) CRT items (Frederick, 2005; Toplak et al., 2011) but not the verbal version of the CRT items. However, the representativeness vignettes were also affected positively by right DLPFC stimulation, while logic index (Stupple et al., 2011; 2013) did not improve. Whilst one cannot rule out the influence of numeracy on the CRT scores, the pattern of stimulation effects on the judgement and decision-making scores seems not to suggest an undue influence of numeracy alone on the current findings.

Limitations of this study were that bilateral montages of the DLPFC areas were used for this investigation of the neural correlates of cognitive reflection and dual-process judgement and decision-making. A bilateral montage makes it difficult to separate effects from anodal and return electrodes. In this experiment bilateral montages were used here because the literature on decision-making with tDCS is very limited, the majority of research on risk-based decision-making has used this bilateral montage (see Chapter 4) (Gorini, Lucchiari, Russell-Edu, & Pravettoni, 2014; Cheng & Lee, 2015). Despite the bilateral montage in this study there was only an improvement in decision-making that tapped inhibitory control (i.e., cognitive reflection test and representativeness) after the anodal stimulation of the right DLPFC (with the return electrode over left DLPFC) compared to the contralateral montage and sham. If an increase in decision-making was the result of the return electrode over the left DLPFC one would expect to the see a significant decrease in decision-making in our left DLPFC group – there was not.

6.7 Summary

This experiment built on the findings of Experiment 1. Here offline stimulation was applied rather than online stimulation (as in Experiment 1). The results revealed that anodal stimulation of the right DLPFC improved judgement and decision-making tasks that require inhibitory control such as the cognitive reflection test and representativeness heuristic problems. The findings extended those of Experiment 1 by increasing the number of cognitive reflection test items so that mathematics / numeracy- and verbal-based items could be analysed separately – the CRT items that required mathematics to complete received a boost from the stimulation whilst the verbal items did not.

The next chapter builds on Experiment 1 and Experiment 2 by examining whether different executive functioning tasks such as the Sternberg task (updating) and Stop Signal Task (inhibition) are modulated by neuromodulation. Furthermore, the total number of CRT items is increased to thirty-two so that there can be a greater sensitivity to the stimulation of numeracy- and verbal-based cognitive reflection.

Chapter 7

The effect of multiple sessions of tDCS modulation on cognitive reflection

7.1 Background

This experiment builds on the results of Experiment 1 (Chapter 5) and 2 (Chapter 6). The results of the first two experiment in chapters 5 and 6 revealed that anodal stimulation of the right DLPFC enhances Type 2 decision-making. Anodal stimulation when administered online (Experiment 1) or offline (Experiment 2) both increase Type 2 thinking for the CRT and representativeness vignettes, however, despite administering multiple tasks to measure updating (2-back and 3-back) and inhibition (AST) no effects of neuromodulation were found for executive functioning.

Although many experiments have reported effects of single-session tDCS on cognition (Hill et al., 2016; Oldrati, Patricelli, Colombo, & Antonietti, 2016) few experiments have investigated the effects of multiple sessions of anodal tDCS on cognition (Lally, Nord, Walsh, & Roiser, 2013; Martin et al., 2013; Richmond, Wolk, Chein, & Olson, 2014; Talsma, Kroese, & Slagter, 2017). In the working memory literature, four studies have administered multiple sessions of tDCS in the investigation of the neural substrates of working memory (Lally et al., 2013; Martin et al., 2013; Richmond et al., 2014; Talsma et al., 2017). Talsma et al., (2017) found an effect of anodal stimulation for a single-session, but no further effect in a second and third session. Whilst, Richmond et al., (2014) found an incremental effect of anodal stimulation after ten sessions that resulted in increased verbal working memory compared to sham. This suggests that there is a cumulative effect of stimulation that carries over from the first session to the second session when the intra-session interval is a maximum of twenty-four-hours (Richmond et al., 2014). The lack of an effect of stimulation from multiple sessions in some studies might be explained by differences in tDCS protocol (e.g., electrode montage, stimulation intensity etc), participant physiology (e.g., skull thickness, hair thickness etc) whereby, the direct current has less resistance when passing through thin hair compared to thick hair, and the duration of experimental cognitive tasks (e.g., n-back versus the Sternberg task – both of which measure working memory (Hill et al., 2016)) - all of these differences result in different rates of efficacy for the neuromodulation between experimental sessions. In this experiment the effects of two sessions of anodal stimulation on cognitive reflection in the dual-process framework was examined.

As in Experiment 2 (Chapter 6) the Cognitive Reflection Test (CRT) (Frederick, 2005), verbal-CRT (Sirota, Kostovicova, Juanchich, Marshall, & Dewberry, 2017) and incongruent base-rate (representativeness) vignettes (Grether, 1980) were administered in this experiment to examine dual-process framework decision-making. Since a between subjects (multivariate analysis of variance) and within subjects (repeated measure analysis of variance) design was used at analyses here, there was an increase in the number of items across these tasks compared to Experiment 2 so that no participant saw the same item twice – seeing the same items more than once would increase the likelihood of a correct Type 2 answer. As variances in CRT performance can be explained by thinking dispositions (Toplak, West, & Stanovich, 2011; Baron, Scott, Fincher, & Metz, 2015) the actively open-minded thinking scale (AOT) (Haran, Ritov, & Mellers, 2013) and rational-experiential inventory (REI)

(Epstein, Pacini, Denes-Raj, & Heier, 1996) were included. Cognitive ability was also recorded and examined using the National Adult Reading Test (NART) (Nelson & Willison, 1991). These measures of thinking dispositions and cognitive ability were previously used in Experiment 2.

Aside from thinking dispositions (Epstein et al. 1996; Haran, Ritov, and Mellers 2013) and cognitive ability (Nelson and Willison 1991), impulsivity can influence judgement and decision-making (Oldrati et al. 2016). In order to control for the potential moderating effects of impulsivity the Barratt Impulsiveness Scale (BIS) was administered (Patton, Stanford, and Barratt 1995). The BIS was chosen as it distinguishes between cognitive inhibition (i.e., the suppression of pre-potent responses) and impulsivity at the motor and behavioural levels. Based on this it was predicted that highly impulsive individuals would perform poorly on the CRT compared to low impulsive individuals.

Next, to examine the role executive functions when Type 2 thinking overrides Type 1 thinking in the dual-process framework different updating and inhibition tasks were administered alongside the n-back. For updating the original (used in Experiments 1 and 2) n-back was used with the additional Sternberg task (Sternberg 1969). Both the n-back and Sternberg tasks are validated measures of updating (Hill, Fitzgerald, and Hoy 2015). To examine inhibition the Stop-Signal Task was administered (Aron et al. 2003). It was predicted that as updating and inhibition are critical functions of the dual-process framework an increase in Type 2 responding should occur when there is an increase in updating and inhibition.

In order to investigate the effects of single-session anodal stimulation and multiple-sessions anodal stimulation on the dual-process framework a mixed between-subjects and within-subjects design was used in this experiment. Anodal stimulation was applied to the right DLPFC or sham. It was hypothesised that anodal tDCS to the right DLPFC would increase Type 2 processing as shown by increased scores in the CRT and incongruent base-rate vignettes compared to sham – this is in accordance with the results of the previous two experiments in this thesis. Next, the second session of stimulation would boost any effects of neuromodulation more than a single-session as evidenced by the cumulative effect of stimulation across experimental sessions in previous studies by Richmond et al., (2014) and Lally, Nord, Walsh, and Roiser, (2013) (see Table 7.1). As for the executive functioning tasks it was hypothesised that working memory (updating) performance as measured by the Sternberg task would improve after right DLPFC stimulation compared to sham. The hypothesis for the stop-signal task which measures inhibition was that the inhibitory control would improve following the stimulation of the right DLPFC compared to sham.

7.2 Research questions

Research question 1

Does offline anodal tDCS of the right DLPFC enhance cognitive reflection as measured by the Cognitive Reflection Test (CRT) and representativeness (incongruent base-rate) vignettes?

Prediction 1: offline anodal stimulation of the right DLPFC will increase Type 2 processing as shown by higher accuracies for the CRT and representativeness vignettes after stimulation compared to sham.

Research question 2

Does offline anodal tDCS of the right DLPFC enhance decision-making in the verbal CRT?

Prediction 2: offline anodal stimulation of the right DLPFC will increase Type 2 processing that does not rely on numeracy as shown by higher accuracies for the verbal-CRT after stimulation compared to sham.

Research question 3

Do multiple anodal stimulation sessions spaced twenty-four-hours apart influence cognitive reflection more than a single stimulation session?

Prediction 3: multiple stimulation sessions spaced in consecutive days will increase Type 2 processing as shown by higher accuracies from day 1 to day 2 for the CRT and representativeness vignettes in the experimental group with two days of stimulation compared to the experimental group with 1 day of stimulation followed by a day of sham.

Research question 4

Do multiple anodal stimulation sessions spaced twenty-four-hours apart influence verbal-CRT scores more than a single stimulation session?

Prediction 4: multiple stimulation sessions spaced in consecutive days will increase Type 2 processing as shown by higher accuracies from day 1 to day 2 for the verbal-

CRT in the experimental group with two days of stimulation compared to the experimental group with 1 day of stimulation followed by a day of sham.

Research question 5

Does offline anodal tDCS of the right DLPFC affect updating (working memory) as measured by the 2-back (n-back) and Sternberg task?

Prediction 5: working memory performance will increase after stimulation as shown by higher accuracies for the 2-back and Sternberg tasks in the stimulation experimental groups compared to sham.

Research question 6

Do multiple anodal stimulation sessions spaced twenty-four-hours apart influence updating (working memory) as measured by the 2-back (n-back) and Sternberg more than a single stimulation session?

Prediction 6: multiple stimulation sessions spaced in consecutive days will increase working memory performance as shown by higher accuracies from day 1 to day 2 for the 2-back and Sternberg tasks in the experimental group with two days of stimulation compared to the experimental group with 1 day of stimulation followed by a day of sham.

Research question 7

Does offline anodal tDCS of the right DLPFC affect inhibition as measured by the Stop Signal Task?

Prediction 7: offline anodal stimulation of the right DLPFC will increase inhibitory control as shown by higher accuracy in the Stop Signal Task after stimulation compared to sham.

Research question 8

Do multiple anodal stimulation sessions spaced twenty-four-hours apart influence inhibition as measured by the Stop Signal Task more than a single stimulation session?

Prediction 8: multiple stimulation sessions spaced in consecutive days will increase inhibitory control as shown by higher accuracies from day 1 to day 2 for the Stop Signal Task in the experimental group with two days of stimulation compared to the experimental group with 1 day of stimulation followed by a day of sham.

7.3 Methodology

7.3.1 Design

This experiment adopted a mixed between-subjects and within-subjects design. Participants in the first two groups completed two sessions each, whilst participants in the sham group completed one session (Table 7.1). The independent between-subjects variable was stimulation polarity (anodal right DLPFC or sham). Stimulation began before the start of behavioural tasks and continued whilst the participants relaxed in a comfortable chair. When the twenty minutes of stimulation ended the tDCS equipment was removed from the participant's head and they began the tasks. All experimental tasks were counterbalanced (Figure 7.1). Single session effects of stimulation (or the absence of an effect) on performance could be ascertained by comparing the first sessions from groups 1 and 3 – the single session of sham was included in this design for this purpose. The second single session effects of stimulation (or absence of an effect) for groups 1 and 2 could also be compared – higher scores in group 1 compared to group 2 would denote an effect of stimulation on performance. A cumulative effect of stimulation across two sessions could be ascertained by comparing both sessions from group 1 – higher scores in the second session in the absence of higher scores in the second session for group 2 would show a cumulative effect of stimulation on performance. Crucially, a comparison of the scores from the tasks in the second session of group 2 compared the first session of the same group could ascertain whether there was a practice effect on performance across the tasks – higher scores on tasks in the second session would suggest that there was a practice effect.

Table 7.1 Procedural design of Experiment 3.

	Sessions	
Group	Session 1	Session 2
1 (a-a)	X	X
2 (a-s)	X	X
3 (sham)	X	

An 'x' denotes the sessions in which participants of a group took part in the experiment. Abbreviations: anodal right dorsolateral prefrontal cortex stimulation (DLPFC) in sessions 1 and 2 (a-a), anodal right DLPFC in session followed by sham in session 2 (a-s).

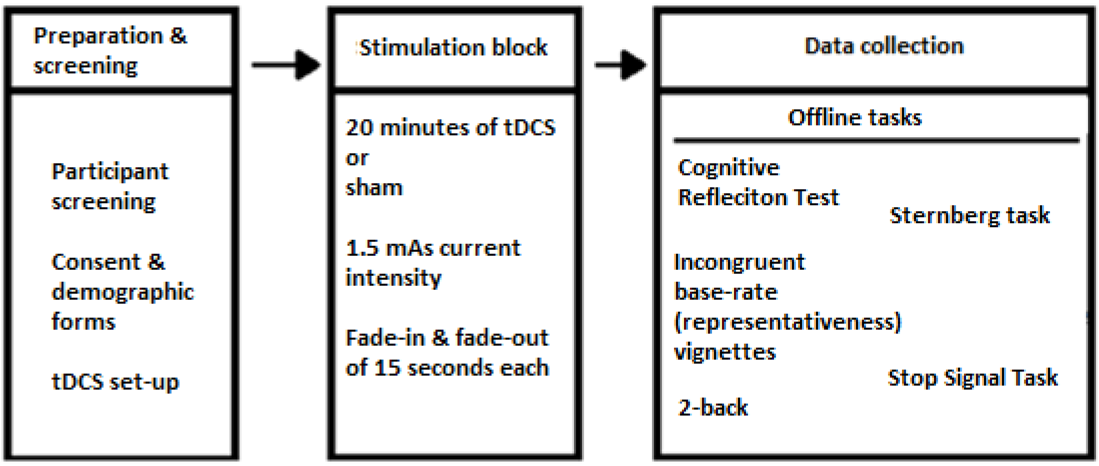


Figure 7.1. Schematic of procedure in Experiment 3. Arrows denote time course. The Cognitive Reflection Test, incongruent base-rate (representativeness) vignettes, 2-back, Sternberg task and Stop signal task issued to participants after twenty minutes of stimulation (offline). All tasks were counterbalanced during data collection.

7.3.2 Participants

Forty-eight participants were recruited through advertising and word-of-mouth at The University of East London (UEL) (mean age = 26.08 ± 0.54 years; 27 females) (Table 7.2). The AOT and REI thinking dispositions were recorded as was cognitive ability (NART) (Table 7.3).

A power analysis calculation using G Power 3.0 revealed that a sample size of 18 participants was needed to reach a significant result. This was based on a medium effect size of $f = 0.30$, according to the convention set out by Cohen (1969, p348), and an alpha (α) significance level of $p = 0.05$ in a within-subjects design experiment with a total of 5 measures and 3 groups.

The inclusion criteria were (i) aged 18 years or above; (ii) fluent English speakers; (iii) right-handed; (iv) naïve to tDCS and (v) naïve to the behavioural tasks used. The exclusion criteria were (i) history of seizures; (ii) family history of seizures; (iii) past or present neurological history; (iv) past or present psychiatric history; (v) past head injury or surgery; (vi) metal implants; (vii) current medication usage; (viii) drug or alcohol dependence; (ix) pregnancy and (x) past training in logic reasoning (e.g., during a university course). All participants provided informed written consent. This experiment was approved by The University of East London (UEL) Research Ethics Committee. After giving consent participants completed all scales and questionnaires (NART, AOT and REI), and the demographic form containing information about sex (male, female or do not wish to say), age, religiosity (1 = not at all religious to 5 = very religious), paranormal beliefs (yes or no) and education level – self reported highest current education level (Tables 7.2 and 7.3). Participants were asked about religiosity based on the dual-process framework literature that suggest that high levels of religiosity positively correlates with high levels of intuitive thinking on the CRT (Pennycook et al., 2012; Razmyar & Reeve, 2013).

Table 7.2. Demographics for all participants.

	Stimulation group (anode location session 1-session 2) mean (SD)		
Demographics	**Right DLPFC-Right DLPFC**	**Right DLPFC-sham**	**Sham**
Sex (M/F)	6/10	7/9	8/8
Age (mean/SD)	25.70 (4.33)	26.70 (3.21)	25.88 (3.91)
Religious (Yes/No)	10/6	5/11	6/10
Education	4.90 (1.60)	5.56 (1.21)	5.38 (1.25)

Education represents the mean qualification level. Abbreviations: Standard Deviations (SD), Dorsolateral prefrontal cortex (DLPFC), females (F), and males (M).

Table 7.3. Cognitive characteristics for all participants.

	Stimulation group (anode location session 1-session 2) mean (SD)		
Cognitive characteristics	**Right DLPFC-Right DLPFC**	**Right DLPFC-sham**	**Sham**
NART score	121.06 (2.81)	121.00 (2.28)	119.31 (2.44)
AOT score	37.81 (6.75)	40.20 (5.13)	42.70 (4.75)
REI 10 R subscale	16.75 (4.83)	15.90 (4.16)	19.75 (3.60)
REI 10 E subscale	14.81 (2.04)	16.00 (2.16)	15.56 (1.63)

The means and standard deviations are presented in parentheses. Abbreviations: Dorsolateral prefrontal cortex (DLPFC), National Adult Reading Test (NART), Actively open-minded thinking (AOT), Rational Experiential Inventory Rational subscale (REI 10 R), Rational Experiential Inventory Experiential subscale (REI 10 E).

7.3.3 tDCS montage and parameters

The same tDCS device, electrode sizes, sham procedure and current intensity (1.5mA) were used as in Experiments 1 and 2. TDCS was delivered using a battery-driven stimulator device (Neuroelectrics, Barcelona) using two sponge electrodes (anodal and return) each circular with a surface area of 25cm^2. The tDCS montage was dependent upon the stimulation group (anode electrode – return electrode): (i) anode right DLPFC return left DLPFC, (ii) sham right DLPFC sham left DLPFC. The electrodes were placed over the right DLPFC (F4) or left DLPFC (F3) according to the EEG 10-20 international system (Herwig, Satrapi, & Schönfeldt-Lecuona, 2003). The ramp-up and ramp-down time were 15 seconds each at the onset and offset of stimulation to decrease the likelihood of discomfort. The sham group consisted of 15 seconds of stimulation at the beginning and end of the 20 minutes.

7.3.4 Materials and measures

All materials used in this experiment were validated and established tasks from the literature. All task items can be found in Appendix C. The Cognitive Reflection Test (Frederick, 2005; Thomson & Oppenheimer, 2016), n-back (Dedoncker et al., 2016; Hill et al., 2016), Sternberg task (Sternberg, 1969; Gladwin, den Uyl, Fregni, & Wiers, 2012) and stop-signal task (Horvath, Forte, & Carter, 2015) have been used in a previous neuromodulation studies (Marshall, Mölle, Siebner, & Born, 2005; Gladwin et al., 2012; Horvath et al., 2015; Oldrati et al., 2016). None of the other tasks included in this experiment have been used in any other neuromodulation experiment. All experimental tasks were counterbalanced (Figure 7.1).

As described in Experiment 2 (Chapter 4) the Cognitive Reflection Test (CRT) was administered in this experiment. The battery used here consisted of a total of thirty-two CRT items which were issued to participants in two parts of sixteen items (Frederick 2005; Toplak, West, and Stanovich 2011; Thomson and Oppenheimer 2016; Szaszi et al. 2017). There was a total of twenty numeracy-based CRT items, with ten items in each of the parts. For the verbal-CRT there was a total of twelve items, with six items in each of the parts. The maximum score for all CRT items (numeracy-based CRT plus the verbal-CRT) when answered correctly was thirty-two. As described in Experiment 2 (Chapter 5) the n-back was used in this experiment. The n-back contained a total of one hundred and twenty trials (correct and incorrect) were presented to participants for a maximum score of thirty.

Scales and questionnaires that record thinking dispositions, as in Chapter 6 were used here. The actively open-minded thinking scale (AOT), Rational Experiential Inventory (REI) and National Adult Reading Test (NART) were all administered prior to stimulation.

As described in Experiment 1 (Chapter 5) the representativeness (incongruent base-rate) vignettes were used in this experiment. A detailed description of the base-rate vignettes follows.

Base-rate vignettes: The base-rate vignettes, also called the representativeness heuristic when administered with an incongruent vignette (Grether, 1980; Teigen & Keren, 2007) demonstrate that when a base-rate (e.g., the probability of independent events occurring) and a vignette (e.g., stereotype of an occupation or age) are presented participants neglect the former in favour of the latter (Kahneman & Tversky, 1972). There are three types of base-rate vignette with vignettes and base-rates that either (i) conflict (incongruent), (ii) do not conflict (congruent), or (iii) are not associated (neutral) (Table 7.4). During this task participants took ten minutes to respond to the ten base-rate vignettes by responding with either the correct probability response or the lure-based stereotype response.

Table 7.4. Examples of each of the types of base-rate vignette.

Type of base-rate vignette	Example base-rate	Example vignette	Answer options
Incongruent	A survey of 1500 people was conducted. Among the participants there were 11 sixteen-year olds and 1489 fifty-year olds.	Ellen is a randomly chosen participant of this survey. Ellen likes to listen to hip hop and rap music. She enjoys wearing tight shirts and jeans. She's fond of dancing and has a small nose piercing.	Option a: Ellen is sixteen years old Option b: Ellen is fifty years old
Congruent	In a study of 700 people there were 615 television reporters and 85 builders.	Ray is a randomly chosen participants of this study. Ray always dresses smartly, liking to wear a suit. He keeps up to date with current affairs and speaks very clearly.	Option a: Ray is a builder Option b: Ray is a television reporter
Neutral	In a study of 1000 people there were 997 people who played the drums and 3 who played the saxophone.	Tom is a randomly chosen participants in this study. Tom is 20 years old. He is studying in Washington and has no steady girlfriend. He just bought a second-hand car with his savings.	Option a: Tom plays the saxophone Option b: Tom plays the drums

These are example base-rate vignettes for demonstration purposes only. The correct answer for each of these examples is option 'b'. In the items used during the experiment the correct answer was not always option 'b'.

A total of twenty base-rate items were given to participants: 10 incongruent, 5 congruent and 5 neutral. The maximum score recorded per participant was 10 (incongruent base-rates).

Sternberg: The Sternberg task measures working memory / updating (Sternberg, 1969). In this task participants are presented with a short-list of 8 letters (e.g., E G H I N **K** O W). After the initial presentation of the stimuli the participant is then shown a letter (e.g., **K**) and asked if the letter had appeared in the short-list of letters.

A total of one hundred and eighty trials (correct and incorrect) were presented to participants with a maximum score of sixty correct answers in sixty matching trials. Participants had a maximum of ten minutes to complete the Sternberg task.

Stop Signal Task: The Stop Signal Task (SST) measures response inhibition (Li, Huang, Constable, & Sinha, 2006; Chikazoe et al., 2009). In this task participants saw an ‘X’ of an ’O’ on screen. They were instructed to press the button that correspondents to the symbol that is presented (e.g., an ‘X’ for an ‘X’). In the second part of the task participants continue to select the buttons, however, if they heard an auditory signal (a beep) they withheld their response by not pressing any button.

A total of three hundred and twenty trials split into four blocks of eighty trials were presented to participants. This task took a maximum of ten minutes to complete.

Barratt Impulsiveness Scale: The Barratt Impulsiveness Scale (BIS) is a measure of impulsivity (Patton, Stanford, & Barratt, 1995). Participants respond to thirty items (e.g., *I don't pay attention*) on a four-point Likert scale from 1 (never/rarely) to 4 (almost always/always). Participants completed the BIS on pen and paper and were limited to a maximum of five minutes to complete this task.

For the executive function tasks – n-back task, Sternberg task and Stop Signal Task – participants completed the same trials in both experimental conditions. For all other tasks participants completed different trials/items in each experimental session.

7.4 Analysis plan

The raw data were screened for outliers and missing values before conducting any analysis. Outliers were identified as data points outside of a 1.5 interquartile (IQR) range. For all judgement and decision-making, and working memory (updating) tasks accuracies (or percentages for the Type 1 analyses) were used during analysis as there were different numbers of items for the CRT, verbal-CRT, and incongruent base-rate vignettes. There was also a different number of trails in the 2-back and Sternberg tasks. There were no missing values.

The first analysis examined whether there were any *a priori* differences between experimental groups regarding cognitive characteristics, as in Experiment 2. A multivariate of analyses of variance (MANOVA) was performed, with type of stimulation (right DLPFC or sham) as between-subject factor. Dependent variables were the actively open-minded thinking scale (AOT), National Adult Reading Test (NART), and the REI subscales: rationale (REI 10 R) and experiential (REI 10 E).

The second analysis examined whether there were any *a priori* differences between experimental groups with regards to Barratt Impulsiveness Scale (BIS). A multivariate analyses of variance (MANOVA) was performed, with type of stimulation (right DLPFC or sham) as the between-subject factor. Dependent variables were the BIS second order subscales, attentional impulsiveness, motor impulsiveness and non-planning impulsiveness.

Next a series of multivariate analyses of variances (MANOVAs) and repeated measures analyses of variances (RM ANOVAs) examined the effects of stimulation on judgement and decision-making tasks, working memory tasks (updating), and inhibition. In the MANOVAs the sum total of correct responses of each variable was used during analysis. For the RM ANOVAs accuracy was used during analysis for each of the variables because of different numbers of items across tasks, e.g., the CRT had ten items whilst the verbal-CRT had six items per session.

7.4.1 Judgement and decision-making analyses

To examine the effects of stimulation on decision-making four separate multivariate analysis of variances (MANOVA) were conducted with stimulation (sham or right DLPFC) as the between-subject factor. In the first MANOVA dependent variables were accuracies for: CRT, verbal-CRT and incongruent base-rate vignettes. In the second

MANOVA dependent variables were the percentage of intuitive incorrect answers for the: CRT, verbal-CRT and incongruent base-rate vignettes. The third and fourth MANOVAs were similar to the first and second with the exception that all dependent variables contained data from the second experimental session. Significant effects were analysed with ANOVAs to determine the specific contributing contrast.

To test the effects of stimulation on decision-making over the two experimental sessions four separate repeated measures analysis of variances (RM ANOVA) were conducted with stimulation (first or second) and thinking task performance (accuracies for: CRT, verbal-CRT and incongruent base-rate vignettes) as within-subject factors. The first two RM ANOVAs examined decision-making in the experimental group with two anodal stimulation sessions across both days. In the first RM ANOVA dependent variables were accuracies for the: CRT, verbal-CRT and incongruent base-rate vignettes. In the second RM ANOVA dependent variables were the percentage of intuitive incorrect answers for the: CRT, verbal-CRT and the incongruent base-rate vignettes. The third and fourth RM ANOVAs differed from the first and second RM ANOVAs above in that the data was from the experimental group that had one anodal stimulation session followed by a sham session – these final analyses tested for a practice effect across stimulation sessions. Significant effects were analysed with ANOVAs to determine the specific contributing contrast.

7.4.2 Executive functioning: working memory (updating) task analyses

The working memory (updating) analyses were set-up the same as in decision-making MANOVAs and RM ANOVAs above with the exception of the dependent variables. Dependent variables were accuracies for the 2-back and Sternberg tasks.

7.4.3 Executive functioning: inhibition task analyses

The inhibition analyses were set-up the same as in decision-making MANOVAs and RM ANOVAs above with the exception of the dependent variables. Dependent variables were stop signal go errors and stop signal stop errors.

7.4.4 Decision-making and impulsivity: Type 2 regression analyses

To test the relationship between stimulation group and BIS impulsivity on the Type 2 responses in the decision-making tasks (CRT, verbal-CRT and incongruent base-rate vignettes) multiple regression analyses were conducted. Both stimulation (dummy-coded) and the BIS impulsivity subscales were used as predictors of decision-making tasks.

7.4.5 Decision-making and impulsivity: Type 1 regression analyses

To test the relationship between stimulation group and BIS impulsivity on the Type 1 responses in the decision-making tasks (CRT, verbal-CRT and incongruent base-rate vignettes) multiple regression analyses were conducted. Again, both stimulation and the BIS impulsivity subscales were entered as predictors of decision-making tasks.

7.5 Results

A first analysis investigated whether there were any *a priori* differences between groups regarding thinking styles. A multivariate analyses of variance (MANOVA) was performed, with the stimulation group (right DLPFC in repeated stimulation, right DLPFC in single stimulation group, or sham) as the between-subject factor. Dependent variables were the REI subscales: rational (REI 10 R) and experiential (REI 10 E), the actively open-minded thinking scale (AOT) and National Adult Reading Test (NART).

A MANOVA with cognitive characteristics as dependent variables showed an effect of stimulation group (Pillai's trace = 0.35, p = 0.03) on thinking disposition. A follow-up ANOVA found that the experimental groups differed in REI 10 R scores, $F(2, 45)$ = 3.70, p = 0.03, partial η^2 = 0.14. Planned contrasts revealed REI 10 R scores were statistically higher for the sham group (M = 19.75, SD = 3.60) compared to the anodal first (with sham second) group (M = 15.88, SD = 4.16) p = 0.01, 95% CI [-6.88, -0.86], but not compared to the anodal first (with a second stimulation) group (M = 16.75, SD = 4.83) *p* = 0.051, 95% CI [-6.01, 0.01].

To examine if there any differences in REI 10 R scores between the anodal first (with sham second) group and anodal first (with a second stimulation) group a t-test was run. The t-test revealed that there was no difference between REI 10 R scores between these stimulation groups, t(30) = 0.55, *p* = 0.32, 95% CI [-2.40, 4.13].

There was no effect of stimulation group on the REI 10 E, AOT or NART scores all *ps* > 0.06. Thus, the three experimental groups did not differ in the cognitive characteristics scores for the REI 10 E, AOT or NART which have previously been associated with judgement and decision-making performance (e.g., Toplak et al., 2011).

The second analyses examined whether there were any *a priori* differences between experimental groups regarding impulsivity. A multivariate analyses of variance (MANOVA) was performed, with the stimulation group (right DLPFC in repeated stimulation, right DLPFC in single stimulation group, or sham) as the between-subject factor. Dependent variables were the Barratt Impulsiveness Scale (BIS) second order subscales were: attentional impulsiveness, motor impulsiveness and non-planning impulsiveness. The MANOVA revealed that there was no effect of stimulation group on BIS impulsivity subscales, all *ps > 0.13*. Therefore, the three experimental groups did not differ in impulsivity for any of the BIS subscales.

Table 7.5. Barrett Impulsiveness Scale (BIS) second order results across experimental groups.

	Stimulation group (anode location session 1-session 2) mean (SD)		
BIS 2nd order factors	**Right DLPFC-Right DLPFC**	**Right DLPFC-sham**	**Sham**
Attentional	17.90 (3.00)	18.25 (4.30)	18.75 (4.14)
Motor	23.70 (3.07)	24.20 (4.55)	24.38 (3.74)
Non-planning	25.75 (4.54)	25.25 (6.01)	24.31 (5.05)

The means and standard deviations are presented in parentheses. Abbreviations: Dorsolateral prefrontal cortex (DLPFC) and Barrett Impulsiveness Scale (BIS).

7.5.1 Judgement and decision-making results

Raw data was screened for outliers and missing values. There were no missing values or outliers in the accuracy scores (i.e., correct response) for the thinking tasks (i.e., CRT, verbal-CRT and incongruent base-rate vignettes / representativeness). All assumptions including data distribution were examined during analysis – unless otherwise stated these were not violated.

To test the effects of stimulation on Type 2 responses (thinking performance) in the first session a multivariate analysis of variance (MANOVA) was performed with type of stimulation (right DLPFC or sham) as between-subject factor. Dependent variables were accuracies for the: CRT, verbal-CRT, and incongruent base-rate vignettes. The Box's test results showed equality of covariance matrices p = 0.70. Using Wilks' Lambda, there was a significant effect of stimulation on thinking task performance, λ = 0.78, F(3, 44) = 4.09, p = 0.01, partial η^2 = 0.21 – performance improved after stimulation of the right DLPFC.

There was no effect of stimulation (M = 3.70, SD = 1.57) on the verbal-CRT, $F(1, 46) = 1.60$, $p = 0.21$, partial $\eta^2 = 0.03$, compared to sham (M = 3.13, SD = 1.26).

The follow-up ANOVA for CRT accuracy revealed that there was an effect of stimulation on CRT performance, $F(1, 46) = 5.00$, $p = 0.03$, partial $\eta^2 = 0.10$. CRT performance was higher after right DLPFC stimulation (M = 4.00, SD = 1.42) compared to sham (M = 3.00, SD = 1.46) (Figure 7.2, panel A).

The follow-up ANOVA for accuracy in the incongruent base-rate vignettes revealed that there was an effect of stimulation on performance, $F(1, 46) = 5.31$, $p = 0.02$, partial $\eta^2 = 0.10$. Performance for the incongruent base-rate vignettes was higher after right DLPFC stimulation (M = 6.70, SD = 2.73) compared to sham (M = 4.63, SD = 3.22) (Figure 7.2, panel B).

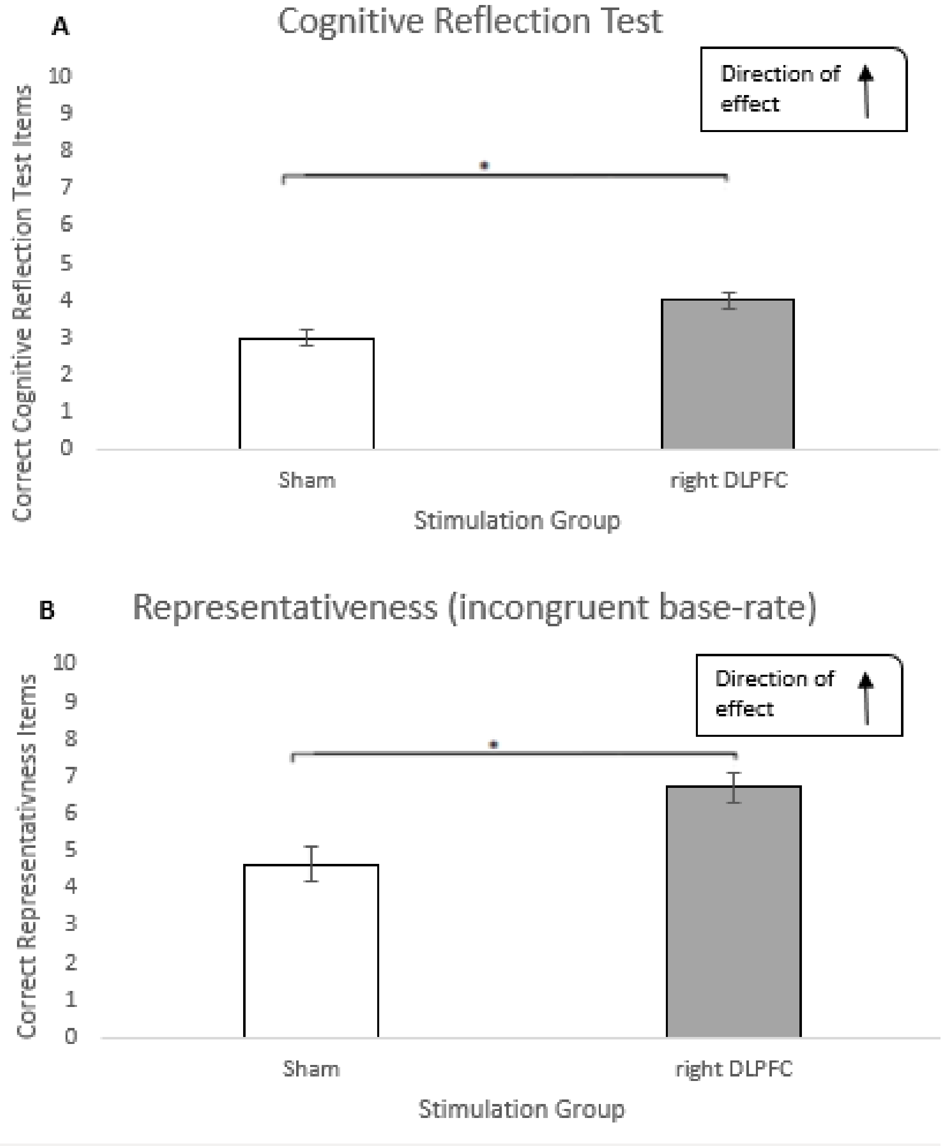


Figure 7.2. Effects of tDCS neuromodulation on thinking task performance. The panels show the effects of tDCS (sham or right DLPFC) on mean correct answers for the Cognitive Reflection Test (panel A) and mean correct answers for representativeness (incongruent base-rate vignettes) (panel B). High values for both panels denote high levels of analytic thinking. Significance levels from follow-up ANOVAs, error bars denote standard errors from mean: an asterisk denotes $p < 0.05$. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC), Cognitive Reflection Test (CRT).*

The second MANOVA examined the effects of stimulation on incorrect, intuitive Type 1 scores in the first session. The between-subject factor was type of stimulation (right DLPFC or sham). Dependent variables were the percentage of intuitive scores for the CRT, verbal-CRT and the incongruent base-rate vignettes. The Box's test results showed equality of covariance matrices, $p = 0.48$. Using Wilks' Lambda, there was no main effect of stimulation on thinking task performance, $\lambda = 0.85$, $F(3, 44) = 2.60$, $p = 0.06$, partial $\eta^2 = 0.15$.

Despite the non-significant result from the MANOVA, a follow-up ANOVA for the percentage of intuitive incongruent base-rate vignettes was performed to be able to compare them to the observed effects in Experiment 1. This revealed an effect of stimulation on these scores, $F(1, 46) = 5.40$, $p = 0.02$, partial $\eta^2 = 0.10$. There were fewer intuitive responses after right DLPFC stimulation ($M = 3.31$, $SD = 2.73$) compared to sham ($M = 5.37$, $SD = 3.22$) (Figure 7.3).

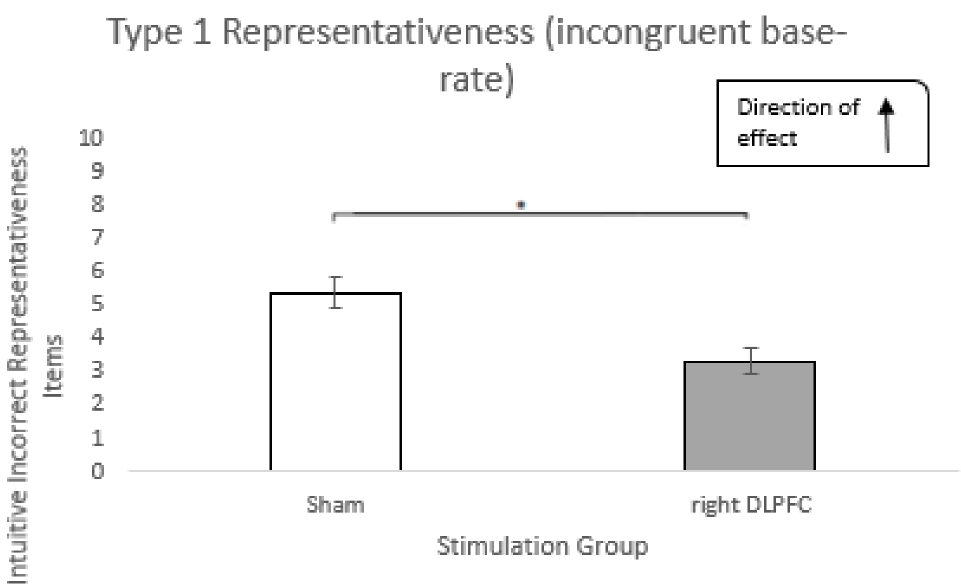


Figure 7.3. Effects of tDCS on intuitive representativeness answers. This figure shows mean incorrect intuitive answers for representativeness (incongruent base-rate) vignettes. High values denote high levels of intuitive thinking. Significance level from follow-up ANOVA, error bars denote standard errors from mean: an asterisk denotes p < 0.05. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC).*

Next, to test the effects of stimulation on Type 2 responses (thinking performance) across the second sessions a multivariate analysis of variance (MANOVA) was performed with type of stimulation (right DLPFC or sham) as between-subject factor. Dependent variables were accuracies for the: CRT, verbal-CRT and the incongruent base-rate vignettes. The Box's test results showed equality of covariance matrices p = 0.92. Using Wilks' Lambda, there was a significant main effect of stimulation on thinking task performance, λ = 0.68, F(3, 28) = 4.36, p = 0.01, partial η^2 = 0.01 – performance improved after stimulation of the right DLPFC compared to sham.

There was no effect of stimulation on performance for the verbal-CRT (stimulation M = 4.75, SD = 1.53, sham M = 3.88, SD = 1.63), F(1, 30) = 2.83, p = 0.10, partial η^2 = 0.08, or the incongruent base-rate vignettes (stimulation M = 6.75, SD = 2.80, sham M = 5.25, SD = 3.00), F(1, 30) = 2.14, p = 0.15, partial η^2 = 0.07.

A follow-up ANOVA for CRT performance revealed that there was an effect of stimulation on the CRT, F(1, 30) = 10.30, p = 0.01, partial η^2 = 0.25. Performance in the repeat sessions was higher for right DLPFC stimulation group (M = 5.56, SD = 2.03) than in the sham group (M = 3.40, SD = 1.66) (Figure 7.4).

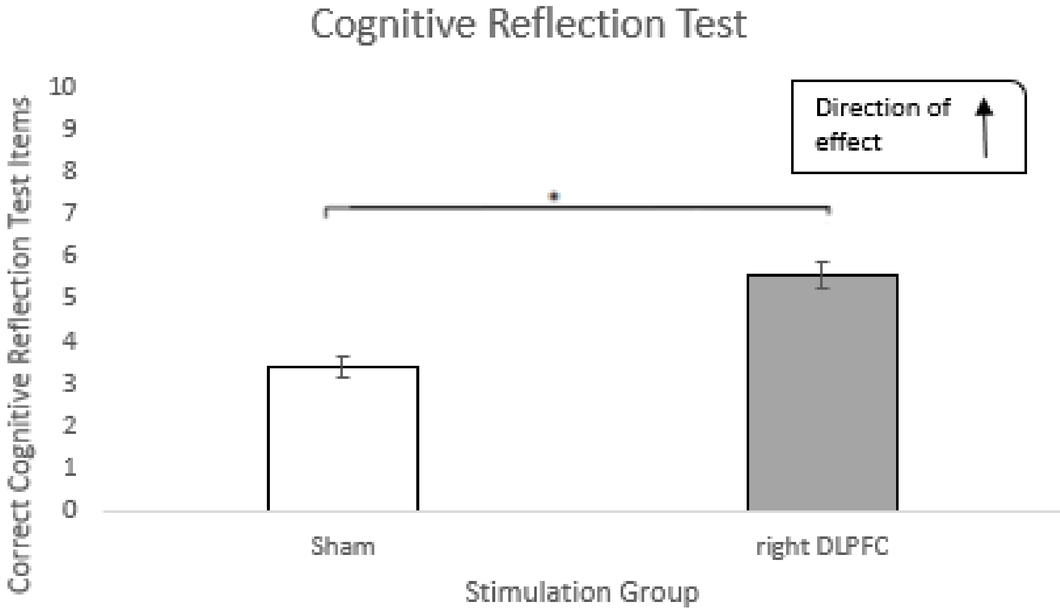


Figure 7.4. Effects of tDCS on cognitive reflection test performance in the second experimental session. This figure shows mean correct answers for the Cognitive Reflection Test. High values denote high levels of analytic thinking. Significance levels from follow-up ANOVAs, error bars denote standard errors from mean: an asterisk denotes $p < 0.05$. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC), Cognitive Reflection Test (CRT).*

The fourth MANOVA examined the effects of stimulation on the percentage of incorrect intuitive Type 1 responses in second sessions of both experimental groups. The between-subject factors was the type of stimulation (right DLPFC or sham). Dependent variables were the percentage of intuitive CRT scores, verbal-CRT and incongruent base-rate vignettes scores. The Box's test results showed equality of covariance matrices $p = 0.78$. Using Wilks' Lambda, there was a significant main effect of stimulation on intuitive thinking task scores, $\lambda = 0.68$, $F(3, 27) = 4.07$, $p = 0.01$, partial $\eta^2 = 0.31$ – there were fewer intuitive responses after the stimulation of the right DLPFC compared to sham.

There was no effect of stimulation group on intuitive answers for the incongruent base-rate vignettes (stimulation M = 3.46, SD = 2.75, sham M = 4.75, SD = 3.00), $F(1, 29) = 1.53$, $p = 0.22$, partial $\eta^2 = 0.05$, or intuitive answers or for verbal-CRT scores (stimulation M = 1.60, SD = 1.30, sham M = 2.37, SD = 1.36), $F(1, 29) = 2.62$, $p = 0.11$, partial $\eta^2 = 0.08$.

The follow-up ANOVA revealed an effect of stimulation group on intuitive CRT scores, $F(1, 29) = 11.20$, $p = 0.01$, partial $\eta^2 = 0.28$ (Figure 7.5). A follow-up t-test revealed that intuitive CRT scores decreased following right DLPFC stimulation (M = 2.06, SD = 1.22) compared to sham $t(28) = 1.05$, $p = 0.01$ (M = 4.00, SD = 1.90).

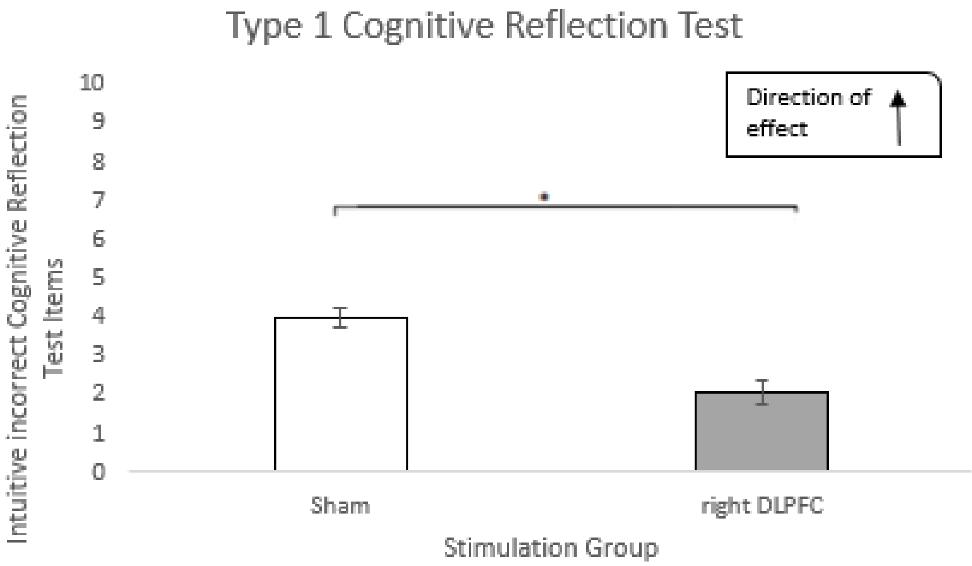


Figure 7.5. Effects of tDCS on incorrect intuitive cognitive reflection test scores in second sessions. This figure shows mean incorrect intuitive answers for the Cognitive Reflection Test. High values denote high levels of intuitive thinking. Significance levels from follow-up ANOVAs, error bars denote standard errors from mean: an asterisk denotes p < 0.05. *Abbreviations: Dorsolateral prefrontal cortex (DLPFC), Cognitive Reflection Test (CRT).*

Next, a repeated measures analyses of variance (RM ANOVA) examined the cumulative effects of stimulation in the experimental group with two anodal stimulation sessions spaced twenty-four-hours apart. Within-subjects variables were stimulation session (first or second) and thinking task (accuracies for: CRT, verbal-CRT and incongruent base-rate vignettes).

There was an effect of stimulation across the two experimental sessions on thinking task performance, $F(1, 15) = 4.50$, $p = 0.05$, partial $\eta^2 = 0.23$. Performance improved in the second session compared to the first session (Figure 7.6).

The follow-up t-test for the CRT scores revealed that performance improved in the second experimental session (M = 0.60, SD = 0.22) compared to the first session (M = 0.41, SD = 0.17), t(15) = -2.80, p = 0.013.

Separate follow-up t-tests revealed that there was no statistically significant difference across experimental sessions for the verbal-CRT (1^{st} session: M = 0.58, SD = 0.23, 2^{nd} session: M = 0.71, SD = 0.20), t(15) = -2.03, p = 0.06, or for the incongruent base-rate vignettes (1^{st} session: M = 0.66, SD = 0.26, 2^{nd} session: M = 0.67, SD = 0.28), t(15) = -0.23, p = 0.82.

There was a 2-way interaction between stimulation session and thinking task, F(2, 30) = 4.70, p = 0.02, partial η^2 = 0.24. As shown above, CRT performance improved across stimulation sessions, with higher performance in the second experimental session than the first session, whereas, there was no difference between first and second session for incongruent base-rate vignette performance (Figure 7.6).

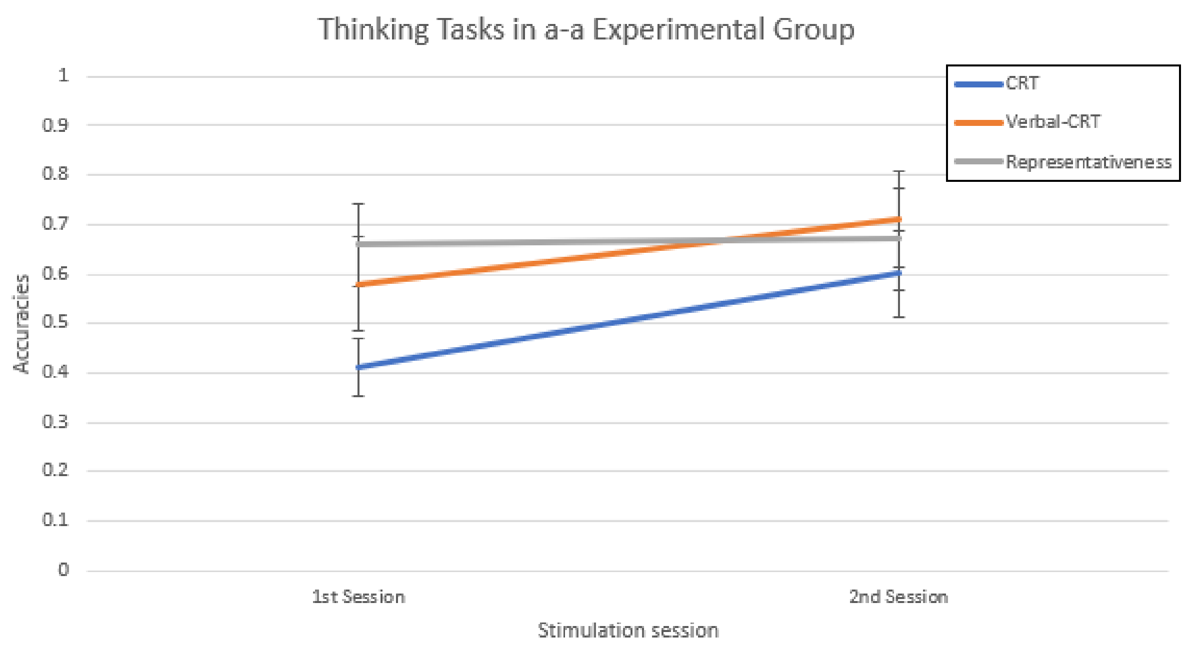


Figure 7.6. Thinking task accuracy across stimulation sessions in the repeated stimulation experimental group. This figure shows accuracy for the CRT, verbal-CRT and representativeness (incongruent base-rate) vignettes across the stimulation sessions in the repeated stimulation group. High values denote high levels of analytic thinking. *Abbreviations: Experimental group with two anodal stimulation sessions (a-a), Cognitive Reflection Test (CRT).*

The second two-way repeated measures ANOVA was run with stimulation session (first or second) and the percentage of intuitive Type 1 thinking task scores (CRT, verbal-CRT and incongruent base-rate vignette) as within-subjects variables.

There was an effect of stimulation across the experimental sessions on intuitive thinking task scores, $F(1,15) = 14.58$, $p = 0.01$, partial $\eta^2 = 0.51$. Intuitive responding decreased in the second session compared to the first session.

A follow-up t-test for intuitive CRT responses revealed that there were fewer intuitive responses in the second stimulation session (M = 0.20, SD = 0.12) than the first session (M = 0.40, SD = 0.18), t(15) = 3.00, *p* = 0.01.

The separate follow-up t-tests for intuitive responses for the verbal-CRT, t(15) = 1.37, *p* = 0.20, and incongruent base-rate vignettes, t(15) = -0.23, *p* = 0.82 revealed no difference in responses across sessions. For the verbal-CRT there was no statistically significant difference in intuitive responses for the first (M= 0.30, SD = 0.23) and second (M = 0.20, SD = 0.20) sessions. There was also no difference in intuitive responding for the incongruent base-rate vignettes across the first (M = 0.66, SD = 0.26) and second (M = 0.67, SD = 0.28) sessions.

There was no 2-way interaction between stimulation session and task, F(2, 30) = 2.03, *p* = 0.15, partial η^2 = 0.12 (Figure 7.7).

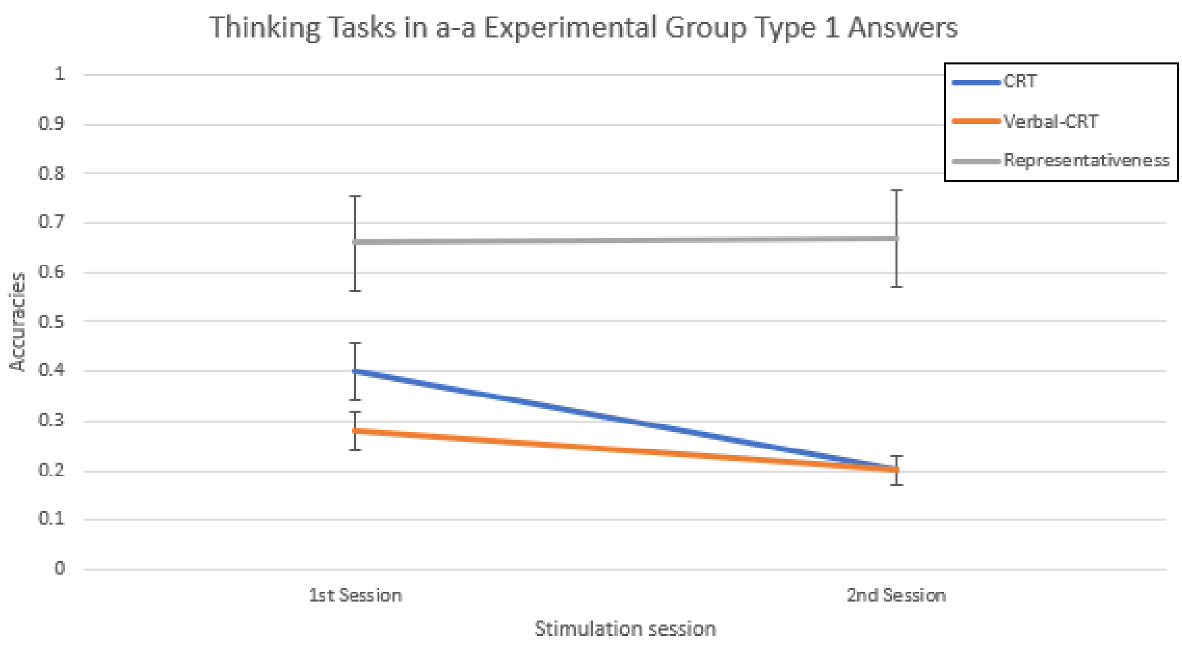


Figure 7.7. Type 1 intuitive thinking task scores as percentages across stimulation sessions in the repeated stimulation experimental group. This figure shows percentage of Type 1 answers for the CRT, verbal-CRT and representativeness (incongruent base-rate) vignettes across the stimulation sessions in the repeated stimulation group. High values denote high levels of analytic thinking. *Abbreviations: Cognitive Reflection Test (CRT), repeated anodal stimulation experimental group (a-a).*

The third RM ANOVA was run to examine if there were any practice effects between sessions in the stimulation first and sham second experimental condition. Within-subjects variables were stimulation session (first or second) and thinking task (accuracies for: CRT, verbal-CRT, and incongruent base-rate vignettes). There were no effects of stimulation session on thinking task performance, $F(1, 15) = 1.60$, $p = 0.22$, partial $\eta^2 = 0.10$.

There was an effect of thinking task across sessions, F(2, 30) = 5.86, p = 0.01, partial η^2 = 0.30. The planned contrasts revealed that accuracy was higher for the incongruent base-rate vignettes (1st session: M = 0.68, SD = 0.30, 2nd session: M = 0.52, SD = 0.30) compared to CRT accuracy (1st session: M = 0.41, SD = 0.13, 2nd session: M = 0.36, SD = 0.18) regardless of stimulation session, F(1,15) = 7.82, p = 0.01. There was no difference in accuracy between the verbal-CRT (1st session: M = 0.56, SD = 0.23, 2nd session: M = 0.58, SD = 0.22) and incongruent base-rate vignettes (1st session: M = 0.68, SD = 0.30, 2nd session: M = 0.52, SD = 0.30), F(1,15) = 0.14, p = 0.71 (Figure 7.8).

There was no statistically significance interaction between stimulation session and task, F(2, 30) = 1.37, p = 0.27, partial η^2 = 0.10 (Figure 7.8).

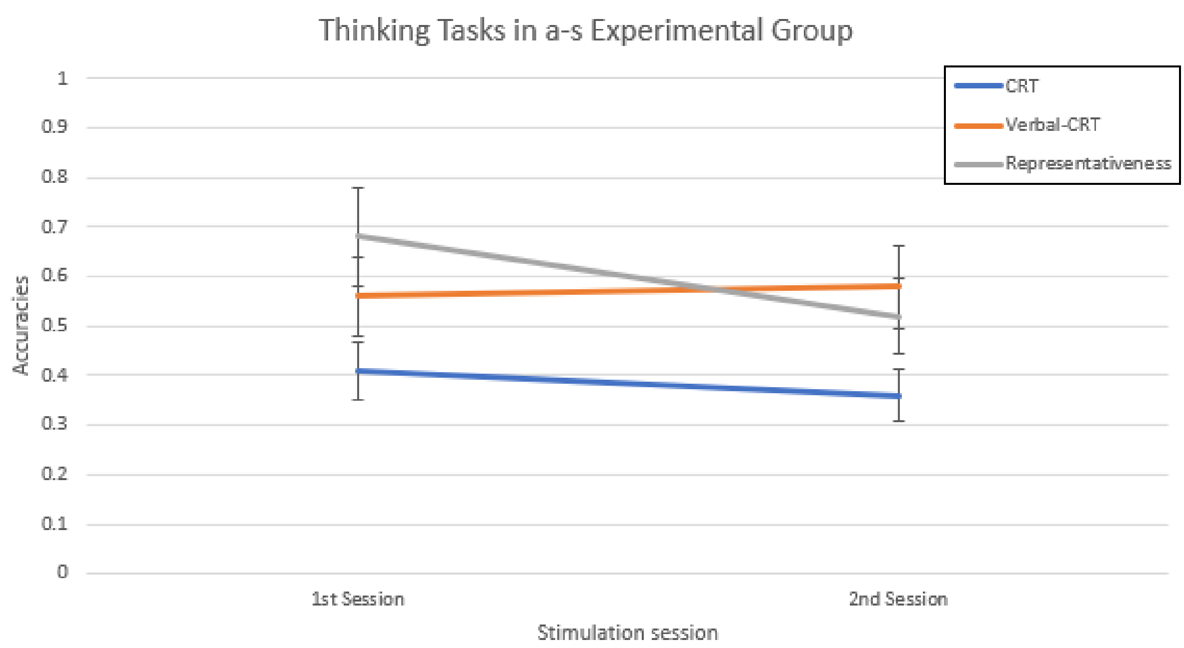


Figure 7.8. Thinking task accuracy across stimulation sessions in the anodal first and sham second experimental group. This figure shows accuracy for the CRT, verbal-CRT and representativeness (incongruent base-rate) vignettes across the stimulation sessions in the anodal first and sham second experimental group. High values denote high levels of analytic thinking. *Abbreviations: Cognitive Reflection Test (CRT), anodal first and sham second experimental group (a-s).*

The final RM ANOVA for the judgement and decision-making tasks examined if there was any practice effect on the percentage of Type 1 intuitive response scores across sessions in the stimulation first and sham second experimental condition. Within-subjects variables were stimulation session (first or second) and intuitive thinking task percentage scores (CRT, verbal-CRT, and incongruent base-rate vignettes). There was no effect of stimulation session on intuitive response scores, $F(1,15) = 1.46$, $p = 0.24$, partial $\eta^2 = 0.08$.

There was an effect of thinking task across sessions $F(2, 30) = 18.32$, $p = 0.01$, partial $\eta^2 = .55$. The planned contrasts revealed that there were fewer intuitive responses for the CRT compared (1st session: M = 0.38, SD = 0.15, 2nd session: M = 0.40, SD = 0.18) to the incongruent base-rate vignettes (1st session: M = 0.67, SD = 0.30, 2nd session: M = 0.52, SD = 0.30), $F(1, 15) = 20.78$, $p = 0.01$, and for the CRT compared to the verbal-CRT (1st session: M = 0.35, SD = 0.22, 2nd session: M = 0.34, SD = 0.20), $F(1, 15) = 22.95$, $p = 0.01$ (Figure 7.9).

There was no statistically significant interaction between stimulation session and task, F(2, 30) = 1.26, p = 0.30, partial η^2 = 0.08 (Figure 7.9).

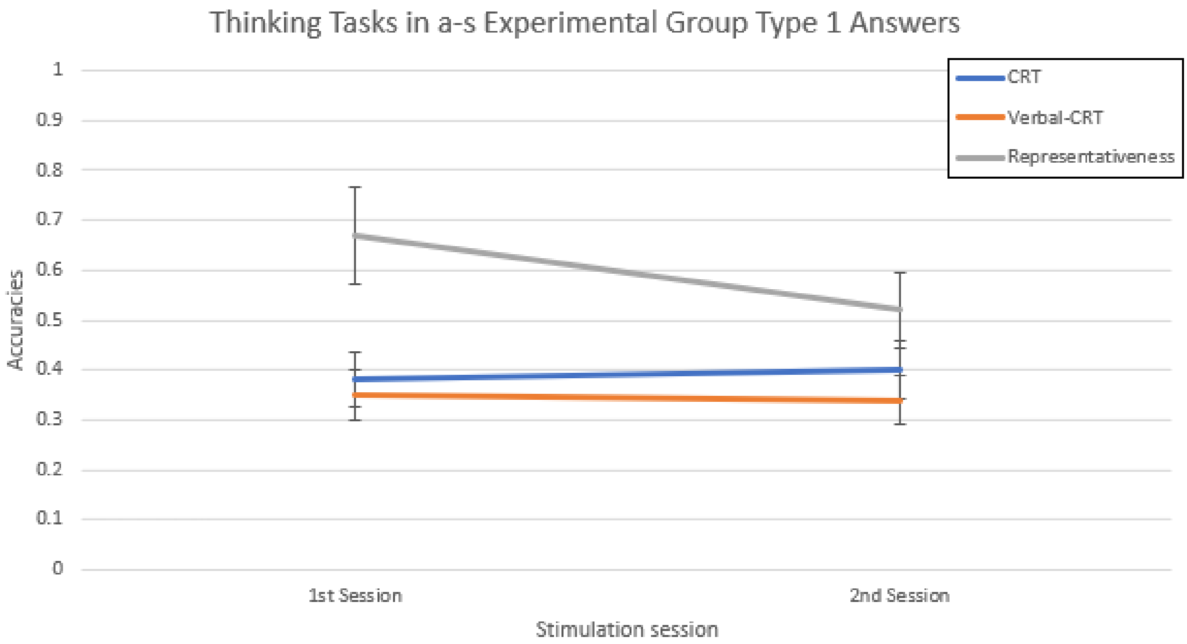


Figure 7.9. Intuitive thinking task scores as percentages across stimulation sessions in the anodal first and sham second experimental group. This figure shows percentage of Type 1 answers for the CRT, verbal-CRT and representativeness (incongruent base-rate) vignettes across the stimulation sessions in the anodal first and sham second experimental group. High values denote high levels of analytic thinking. *Abbreviations: Cognitive Reflection Test (CRT), anodal first and sham second experimental group (a-s).*

7.5.2 Executive function: working memory (updating) results

To test the effects of stimulation on working memory accuracy in the first session a multivariate analysis of variance (MANOVA) was performed with type of stimulation (right DLPFC or sham) as between-subject factor. Dependent variables were the percentage of correct answers for the 2-back and Sternberg tasks. The Box's test results showed equality of covariance matrices $p = 0.40$. Using Wilks' Lambda, there was no main effect of stimulation on working memory performance, Wilks' $\lambda = 0.92$, $F(2, 45) = 1.86$, $p = 0.16$, partial $\eta^2 = 0.07$. There were no effects of stimulation on 2-back correct answers, $F(1, 46) = 0.90$, $p = 0.35$, partial $\eta^2 = 0.02$ or Sternberg correct answers, $F(1, 46) = 2.22$, $p = 0.14$, partial $\eta^2 = 0.04$.

To examine the effects of stimulation on working memory accuracy a multivariate analysis of variance (MANOVA) was performed with type of stimulation (right DLPFC or sham) as between-subject factor. Dependent variables were the percentage of correct answers for the 2-back and Sternberg tasks. The Box's test results showed that the equality of covariance had been violated $p = 0.04$ so Pillai's trace was used. Using Pillai's Trace, there was no main effect of stimulation on working memory performance, Pillai's trace = 1.26, $F(2, 29) = 1.26$, $p = 0.30$, partial $\eta^2 = 0.08$. There were no effects of stimulation on 2-back correct answers, $F(1, 30) = 2.00$, $p = 0.17$, partial $\eta^2 = 0.06$ or Sternberg correct answers, $F(1, 30) = 1.58$, $p = 0.21$, partial $\eta^2 = 0.05$.

Next, a repeated measures ANOVA was run with stimulation session (first or second) and working memory performance (the percentage of correct answers in the: 2-back and Sternberg tasks) as within-subjects variables. There was no main effect of stimulation session on working memory performance, $F(1, 15) = 0.01$, $p = 0.96$, partial $\eta^2 = 0.01$.

There was a main effect of type of working memory task across stimulation sessions, $F(1, 15) = 36.56$, $p = 0.01$, partial $\eta^2 = 0.71$. The planned contrasts revealed that there was a difference between the n-back (1st session: M = 0.65, SD = 0.15, 2nd session: M = 0.65, SD = 0.18) and Sternberg (1st session: M = 0.88, SD = 0.06, 2nd session: M = 0.88, SD = 0.05) with higher accuracy for the Sternberg task, $p = 0.01$.

There was no 2-way interaction between stimulation session and working memory task, $F(1, 15) = 0.08$, $p = 0.78$, partial $\eta^2 = 0.01$.

The second RM ANOVA examined if there was a practice effect between sessions in the stimulation first and sham second experimental condition. Within-subjects variables were stimulation session (first or second) and working memory performance (percentage of correct answers for the 2-back and Sternberg tasks). There was no main effect of stimulation session on working memory performance, $F(1, 15) = 0.28$, $p = 0.60$, partial $\eta^2 = 0.02$.

There was a main effect of type of working memory task across stimulation sessions, $F(1, 15) = 77.01$, $p = 0.01$, partial $\eta^2 = 0.83$. The planned contrasts revealed that there was a difference between the n-back (1st session: M = 0.60, SD = 0.16, 2nd session: M = 0.58, SD = 0.15) and Sternberg (1st session: M = 0.86, SD = 0.07, 2nd session: M = 0.84, SD = 0.10) with higher accuracy for the Sternberg task $p = 0.01$. There was no 2-way interaction between stimulation session and working memory performance, $F(1, 15) = 0.81$, $p = 0.80$, partial $\eta^2 = 0.01$.

7.5.3 Executive function: inhibition results

The first MANOVA to examine inhibition data was performed with type of stimulation (right DLPFC or sham) as between-subject factor. Dependent variables were stop signal task go errors and stop signal task stop errors. The Box's test results showed equality of covariance was violated so Pillai's trace was used. Using Pillai's trace, there was no main effect of stimulation on performance, Pillai's trace = 0.05 $F(2, 45) = 1.31$, $p = 0.28$, partial $\eta^2 = 0.05$. There were no main effects of stimulation on type of error for the stop signal task go errors, $F(1, 46) = 0.51$, $p = 0.48$, partial $\eta^2 = 0.01$ or stop signal task stop errors, $F(1, 46) = 1.26$, $p = 0.26$, partial $\eta^2 = 0.02$.

To test the effects of stimulation on inhibition in the second session a multivariate analysis of variance (MANOVA) was performed with type of stimulation (right DLPFC or sham) as between-subject factor. Dependent variables were stop signal task go errors and stop signal task stop errors. The Box's test results showed equality of covariance matrices $p = 0.91$. Using Wilks' Lambda, there was no main effect of stimulation on performance, Wilks' $\lambda = 0.96$ $F(4, 88) = 0.44$, $p = 0.77$, partial $\eta^2 = 0.02$. There were no effects of stimulation on types of error for the stop signal task go errors, $F(2, 45) = 0.50$, $p = 0.61$, partial $\eta^2 = 0.02$ or stop signal task stop errors, $F(2, 45) = 0.45$, $p = 0.64$, partial $\eta^2 = 0.02$.

Next, a repeated measures ANOVA was performed with stimulation session (first or second) and inhibition (stop signal task go errors and stop signal stop errors) as within-subjects variables. There were no main effects of stimulation session on performance,

$F(1, 15) = 0.61$, $p = 0.44$, partial $\eta^2 = 0.04$ or no main effects of type of error across stimulation sessions, $F(1, 15) = 3.16$, $p = 0.10$, partial $\eta^2 = 0.17$.

There was no 2-way interaction between stimulation session and error type, $F(1, 15) = 1.20$, $p = 0.30$, partial $\eta^2 = 0.07$.

The final repeated measures ANOVA examined if there was a practice effect between sessions in the stimulation first and sham second experimental condition. Within-subjects variables were stimulation session (first or second) and error type (stop signal task go errors and stop signal stop errors). There was no significant main effect of stimulation across sessions on performance, $F(1, 15) = 3.60$, $p = 0.07$, partial $\eta^2 = 0.20$.

There was an effect of type of error across stimulation sessions, $F(1, 15) = 10.13$, $p = 0.01$, partial $\eta^2 = 0.40$. The contrasts revealed that there were more stop errors (1^{st} session: M = 90.62, SD = 54.30, 2^{nd} session: M = 80.46, SD = 36.80) than go errors (1^{st} session: M = 34.63, SD = 98.92, 2^{nd} session: M = 13.54, SD = 27.61). There was no 2-way interaction between stimulation session and inhibition task, $F(1, 15) = 0.13$, $p = 0.72$, partial $\eta^2 = 0.01$.

There was no 2-way interaction between stimulation session and inhibition task, $F(1, 15) = 0.13$, $p = 0.72$, partial $\eta^2 = 0.01$.

7.5.4 Decision-making and impulsivity: Type 2 regression results

The first multiple linear regression was calculated to predict CRT performance based on stimulation group (right DLPFC or sham) and BIS subscales. In the first model – with only stimulation group (dummy coded) as sole predictor - a significant regression equation was found for stimulation group, F(1, 46) = 4.85, *p* = 0.03, with an R^2 of 0.10. Stimulation predicted CRT performance with increased Type 2 responding after stimulation compared to sham, β = -0.97, 95% CI [-1.85, -0.08]. The regression equation was not significant for the second model, F(4, 43) = 2.17, *p* = 0.08, which also included the 3 BIS subscales, with an R^2 of 0.17 – none of the BIS subscales predicted CRT performance.

The second multiple linear regression was calculated to predict verbal-CRT performance based on stimulation group (right DLPFC or sham) and BIS subscales. In the first model there was no significant regression equation for stimulation group, F(1, 46) = 1.54, *p* = 0.22, with an R^2 of 0.03. The regression equation was also not significant for the second model, F(4, 43) = 0.60, *p* = 0.67, with an R^2 of 0.22 – none of the BIS scales predicted verbal-CRT performance.

The final multiple linear regression was calculated analogue to the above to predict incongruent base-rate vignette (representativeness) performance based on stimulation group (right DLPFC or sham) and BIS subscales. In the first model a significant regression equation was found for stimulation group, F(1, 46) = 5.40, *p* =

0.02, with an R^2 of 0.10. Stimulation predicted incongruent base-rate vignette performance with increased Type 2 responding after stimulation compared to sham, β = -0.32, 95% CI [-3.85, -0.27]. The regression equation was not significant for the second model, F(4, 43) = 1.93, p = 0.12, with an R^2 of 0.15 – none of the BIS subscales predicted CRT performance.

7.5.5 Decision-making and impulsivity: Type 1 regression results

A multiple linear regression was calculated to predict intuitive Type 1 CRT scores based on stimulation group (right DLPFC or sham) and BIS subscales. In the first model there was no significant regression equation for stimulation group, F(1, 46) = 0.30, p = 0.60, with an R^2 of .-0.01. The regression equation was not significant for the second model which also included the 3 BIS subscales, F(4, 43) = 0.21, p = 0.93, with an R^2 of -0.02 – none of the BIS subscales predicted intuitive CRT scores.

The second multiple linear regression was calculated to predict intuitive Type 1 verbal-CRT scores based on stimulation group (right DLPFC or sham) and BIS subscales. In the first model there was no significant regression equation for stimulation group, F(1, 46) = 0.70, p = 0.41, with an R^2 of 0.01. The regression equation was not significant for the second model containing the 3 BIS subscales, F(4, 43) = 1.04, p = 0.46, with an R^2 of 0.04 – none of the BIS subscales predicted intuitive verbal-CRT scores.

The final multiple linear regression was calculated to predict intuitive Type 1 incongruent base-rate vignette (representativeness) scores based on stimulation group (right DLPFC or sham) and BIS subscales. In the first model a significant regression equation was found for stimulation group, F(1, 46) = 5.40, *p* = 0.02, with an R^2 of 0.10. Stimulation predicted intuitive Type 1 incongruent base-rate vignette scores with decrease in Type 1 responding after stimulation compared to sham, β = 0.32, 95% CI [0.27, 3.85]. The regression equation was not significant for the second model which also included the 3 BIS subscales, F(4, 43) = 1.93, *p* = 0.12, with an R^2 of 0.15 – none of the BIS subscales predicted intuitive CRT scores.

In summary, using the BIS, impulsivity was not found to be a significant predictor of judgement and decision-making performance across types of tasks and scores.

7.6 Discussion

Experiment 3 replicated many of the basic effects in Experiment 1 (Chapter 5) and Experiment 2 (Chapter 6). There was an effect of anodal stimulation over the right DLPFC on cognitive reflection after one session (offline) as in Experiment 1 (Chapter 5) and Experiment 2 (Chapter 6). Type 2 cognitive reflection, as measured with the CRT and incongruent base-rate vignettes increased after the enhancement of cortical excitability in the right DLPFC following a single session of stimulation. Other crucial findings of this experiment were that multiple anodal stimulation sessions with a twenty-four-hour intra-session interval resulted in a cumulative boost in cognitive reflection, as measured by the CRT (but not the incongruent base-rate vignettes). The key finding was the increased cognitive reflection between first and second stimulation provides some evidence of a cumulative effect of neuromodulation. Importantly, there was no substantial practice effect on decision-making tasks over the two experimental sessions.

The main predictions were as in Chapter 6, that increasing cortical excitability of the right DLPFC would increase performance on judgement and decision-making tasks that presumably rely on the inhibition of Type 1 automatic processing (Evans, 2003; Stanovich, 2009). The findings support the results of Experiment 2 (Chapter 6) which show that cognitive reflection (Type 2) was boosted for the mathematical CRT and incongruent base-rate vignettes, but not for the verbal-CRT compared to sham (Frederick, 2005; Sirota et al., 2017). These accuracy levels are also higher than the accuracies for papers that do not use brain stimulation methods (Frederick, 2005; Toplak, 2014; Sirota et al., 2017).

The second main prediction was that applying anodal stimulation to the right DLPFC in two sessions of stimulation spaced twenty-four-hours apart would produce an additional increase in cognitive reflection. This was based on the idea that multiple stimulation sessions would have a cumulative effect on cognitive reflection as in the clinical literature (Talsma et al., 2017; Gilmore, Dickmann, Nelson, Lamberty, & Lim, 2018) for other tasks. One paper that found an cumulative effect of multiple stimulation sessions, with no effect in a single session, showed that fifteen anodal stimulation sessions of the right DLPFC are needed to reduce risky decision-making in the BART (see Chapter 4) by decreasing impulsiveness (Gilmore et al., 2018). Although the paper by Gilmore et al., uses a clinical sample this provides some evidence of the similar cumulative effect of stimulation that also increased cognitive reflection in this experiment. In this experiment the results suggest that there is a cumulative effect of stimulation on cognitive reflection when the stimulation is applied over the right DLPFC.

The final prediction was that the cumulative effect of anodal stimulation on the right DLPFC for the CRT and incongruent base-rate vignette scores would surpass any practice effect (Lemay, Bédard, Rouleau, & Tremblay, 2004; Talsma et al., 2017). When a participant completes an identical task more than once their performance gradually often increases in step with the number of times that they perform the task until a ceiling effect is reached (i.e., the practice effect) (Lindsay & Jacoby, 1994; Donovan & Radosevich, 1999). In this experiment, the second experimental group (with one session of anodal stimulation followed by sham) was used to assess if there was any practice effect across all tasks. If a practice effect was present then participants would perform better in the second experimental session than the first session (e.g., higher CRT scores in the second session compared to the first) - they did not. There was no practice effect on decision-making tasks or executive functioning in this experiment. Therefore, adapting an experimental design with the addition of this second group eliminates a confounding practice effect whilst confirming that the cumulative effect of anodal stimulation was the source of the increase in cognitive reflection across experimental sessions.

The increase in cognitive reflection after right DLPFC stimulation could not be explained by cognitive characteristics such as thinking disposition, cognitive ability or impulsivity (BIS) as none of the relevant analyses revealed any effects on Type 2 thinking. Furthermore, the measures of updating (Sternberg and 2-back) and inhibition (SST) that were administered to capture executive functioning also revealed no effects of stimulation on these variables. A review of forty-three studies by Toplak et al., (2010) suggests that although many studies report correlations between thinking dispositions, cognitive ability, executive functions and cognitive reflection only a small proportion of these experiments actually reveal a significant relationship between decision-making and these variables.

Limitations of this study were the bilateral montages of the DLPFCs which were used to examine the neural correlates of cognitive reflection and dual-process judgement and decision-making. The bilateral montage was used here to build on the results from the meta-analysis (Chapter 5) and Experiment 1 (Chapter 6). Some researchers may consider that the bilateral montage, with electrodes of the right and left DLPFCs would leave the question of whether any effect on cognitive reflection is the direct result of anodal stimulation or the right DLPFC, or the anodal stimulation of the right DLPFC with a return over the left DLPFC (i.e., the return electrode contributing to the effect). Measures were taken in Experiment 2 to account for the potential effect of the contralateral return electrode on cognitive reflection and executive function scores. As there was no decrease in cognitive reflection in the left DLPFC experimental group in Experiment 2 the effects of stimulation in this experiment were likely not a result of the return electrode over the left DLPFC (see Chapter 6). The final limitation was that due to time constraints the cumulative effects of stimulation were observed over only two experimental sessions – given more time the total number of experimental sessions could be increased to investigate this cumulative effect of stimulation further (see Talsma et al., 2017; Gilmore et al., 2018).

7.7 Summary

This experiment built on the findings of Experiments 1 and 2. Offline stimulation was applied to the right DLPFC in a mixed between-subjects and within-subjects experimental design so that: (i) a replication of Experiment 2 results on cognitive reflection could be tested, (ii) the effects of multiple sessions of anodal stimulation on cognitive reflection could be examined, and (iii) practice effects across decision-making and executive functioning tasks could be eliminated. The results replicated and extended those of Experiments 1 and 2 – offline anodal stimulation of the right DLPFC continued to increase cognitive reflection after a single stimulation session when more test items were added. Furthermore, the multiple anodal stimulation sessions with a twenty-four-hour intra-session interval revealed that the second session of stimulation enhanced cognitive reflection further than a single session – this provides some evidence of a cumulative effect of stimulation carrying over from the first session to the second. The influence of practice effects on cognitive reflection was eliminated as the source of the boost on cognitive in the second stimulation session.

Chapter 8

8.1 General Discussion

The meta-analysis and three experiments in this thesis demonstrate that anodal neuromodulation of the frontal lobe affects performance on judgement and decision-making tasks. The meta-analysis revealed that anodal stimulation of the left frontal lobe (FL) (orbital frontal cortex, inferior frontal cortex and DLPFC) significantly improved decision-making performance and reduced risk-taking behaviour. The three experimental studies then examined the dual-process framework with tasks designed to measure different components of the framework (inhibition, set-shifting and updating) more precisely. Rather than reducing Type 1 processing, as in the meta-analysis, anodal stimulation of the right DLPFC enhanced analytic Type 2 processing without always reducing Type 1 thinking. Taken together the four studies (including the meta-analysis) provide evidence that that the neural substrates of judgement and decision-making that are involved in Type 2 processing (e.g., CRT) are localised in the right DLPFC.

The meta-analysis (Chapter 4) examined the effects of anodal and cathodal stimulation on the dual-process framework of decision-making. In this chapter there were sub-group analyses on risk-taking decision-making, Type 1 decision-making and Type 2 decision-making – each of these sub-groups also assessed online versus offline stimulation and right versus left FL stimulation. The results revealed that online anodal stimulation of the left FL had a significant effect on decision-making, reducing the use of Type 1 processing. One explanation for the reduction in Type 1 processing is that the left FL supports the convergence of interconnections with other brain structures that coordinate planning and problem solving (Hecht, Walsh, and Lavidor, 2010; Cheng and Lee, 2015). Secondly, the left FL is associated with cognitive functions that are important in impulsive decision-making such as self-regulation (or self-control) (Mengarelli et al., 2015) and affective modulation (Hare, Camerer, and Rangel, 2009), as both affective modulation and self-regulation are associated with this type of thinking. For example, when in a highly affective (i.e., emotional) state one is likely to make an impulsive decision rather than a calm and calculated decision (Hare, Camerer, and Rangel, 2009). Interestingly, there was no significant effect on Type 2 processing which may be due to the limitations of this meta-analysis.

The second main finding from the meta-analysis was that online anodal stimulation of the left DLPFC reduced risky decision-making. Unlike the sub-group analyses for Type 1 and Type 2 processing most of the papers in the risk-taking analysis used the same experimental task, the BART (four of five used the BART). These findings have been corroborated with a recently published study that replicated these results by Nejati, Salehinejad, and Nitsche (2018). The reduction in risk-taking can be explained through the dual-process framework of decision-making. Impulsive risky decision-making relies on automatic Type 1 processing (Evans, 2006; 2012). To suppress risky decision-making, one must override these decisions by engaging in analytic Type 2 thinking (Nejati, Salehinejad, and Nitsche, 2018). Therefore, it is probably due to shared neural substrates of risky decision-making and Type 1 processing that anodal stimulation of the left DLPFC reduces risk-taking.

Experiment 1 (Chapter 5) provided the first empirical evidence of an increase of cognitive reflection (Type 2 thinking) during neuromodulation. In this experiment, online anodal stimulation was administered whilst participants completed a battery of decision-making tasks that included belief bias syllogisms, the CRT and representativeness vignettes. There was an effect of stimulation on performance for the CRT and representativeness vignettes with Type 2 cognitive reflection performance increasing after anodal stimulation of the right DLPFC. A further analysis of the incorrect intuitive Type 1 responses for the representativeness vignettes revealed a reduction in Type 1 processing after the anodal neuromodulation of the right DLPFC. These findings can in principle be explained by the involvement of the right DLPFC in inhibition (Aron, Robbins, and Poldrack, 2004; Bari and Robbins, 2013) and set-shifting (Loftus et al., 2015) – both of which are executive functions that underpin decision-making in the dual-process framework (Evans, 2008; Friedman and Miyake, 2017). However, although two executive function tasks were used in this experiment to assess updating (the n-back) and inhibition (the numerical Stroop) neither task captured the exact executive functions that are proposed to be involved in the dual-process framework.

It was then tested whether working memory tasks in which high levels of updating are needed for the successful completion such as the 3-back or Sternberg task (Sternberg, 1969; Katsoulaki, Kastrinis, and Tsekoura, 2017) may capture updating more efficiently than arguably easier tasks such as the 2-back (Jaeggi et al., 2010; Friedman and Miyake, 2017). Experiments 2 and 3 therefore used multiple updating and inhibition tasks to better capture the potential relationship between these executive functions and dual-process decision-making (including cognitive reflection).

The second experiment (Chapter 6 – Experiment 2) again showed that stimulating the right DLPFC with offline stimulation (rather than online stimulation in Experiment 1) increased cognitive reflection. As in the first experiment, however, these findings could not be explained by the involvement of the executive functions – namely inhibition (Bari and Robbins, 2013), updating (Jaeggi et al., 2010) and set-shifting (Loftus et al., 2015). There was an effect of stimulation on Type 1 processing in this experiment for the representativeness vignettes, but not for the CRT items.

An important point in Experiment 2 is that, rather than using online stimulation, as in Experiment 1, offline stimulation was used. Where Experiment 1 used online stimulation for the judgement and decision-making tasks (CRT and heuristics) with offline stimulation for the executive functioning tasks, Experiment 2 used offline stimulation for all tasks. Offline stimulation was chosen here for two reasons (i) the meta-analysis indicated that offline stimulation effects intuitive (Type 1) processing but not online, and (ii) that offline stimulation has potentially more applied value as it promises more long-term modulation of behaviour. Crucially, as with the online stimulation in Experiment 1 there was an effect of offline stimulation in Experiment 2 on Type 2 processing – both modes of neuromodulation increased cognitive reflection. A possible explanation for the mechanisms of online and offline stimulation on the neural substrates of Type 2 processing is given in Chapter 2. In short, online stimulation preferentially affects the task-relevant activated neurons (Coffman et al., 2012; Bikson and Rahman, 2013) whilst offline stimulation modulates the neuronal populations independent from, and prior to, the tasks – this distinction does not eliminate the involvement of the neuronal population in the said task (Nitsche et al., 2003; 2008).

Interestingly, and surprisingly, the absence of an effect of stimulation of the right DLPFC for executive functioning from Experiment 1 was also observed in Experiment 2. In Experiment 2 updating was measured with the 2-back and 3-back versions of the n-back (Lally et al., 2013), and inhibition was examined with the Attention Switching Task (AST) (Hanania and Smith, 2010). As discussed in previous chapters, one reason for the lack of effect of stimulation on updating may be that the n-back task does not capture the type of updating that is involved in Type 2 decision-making – experiment 3 tested this hypothesis. With reference to inhibition tasks such as the AST – an additional task introduced in Experiment 3 - some scholars have suggested that there are different forms of inhibition which are measured across the established measures of inhibition such as the Go / No-go task (Aron, Robbins, and Poldrack, 2014), Stop Signal Task (SST) (Boehler et al., 2010) and AST (Hanania and Smith, 2010). The AST was used to measure a type of planned inhibition (also called 'far inhibition') whereby a participant has the chance to see an instruction a short time before the appearance of the task stimulation and therefore prepare their response (Hanania and Smith, 2010). Whilst the SST measures unplanned inhibition (also called 'near inhibition'), as participants do not have the time to prepare a response due to seeing the instruction at the same time as the test stimuli (Swick, Ashley, and Turken, 2011). Experiment 3 examined the relationship between near inhibition and cognitive reflection by administering the SST.

The third experiment (Chapter 7 - Experiment 3) replicated the results of Experiment 2 by showing that offline anodal stimulation of the right DLPFC increased cognitive reflection when this form of Type 2 processing is measured by the CRT and representativeness (also called incongruent base-rate) vignettes (Grether, 1980;

Frederick, 2005). As in the previous two experiments there was no indication of an involvement of the right DLPFC in executive functioning performance that may have underpinned Type 2 processing. Interestingly, there was an effect of anodal stimulation on Type 1 processing for the CRT – intuitive thinking decreased after the neuromodulation of the right DLPFC compared to sham. The reason why there was an effect of stimulation on Type 1 processing here, but not in Experiment 2, may be that in the second experiment there were fewer CRT items. Crucially, whilst there was no effect of stimulation on Type 1 intuitive scores for the CRT with a single session of stimulation (in both Experiments 2 and 3) there was a reduction in intuitive thinking following two sessions of stimulation (as in Experiment 3). This pattern of results provides evidence for the reduction of Type 1 thinking (for the CRT) which only occurs as a result of a cumulative effect of stimulation from a minimum of two sessions of neuromodulation.

The second aim of Experiment 3 was to assess whether there was a cumulative effect of stimulation (Talsma, Kroese, and Slagter, 2017; Gilmore et al., 2018) on the neural substrates of the dual-process framework of decision-making – does cognitive reflection increase in a stepwise manor with the increased quantity of stimulation sessions? The results of this experiment revealed that cognitive reflection does increase after a second session of stimulation as if it increases with each step. Moreover, the same cumulative effect of stimulation was present in the Type 1 analyses when intuitive responding decreased even more in a second session of stimulation than a single session. One possible alternative explanation for the apparent cumulative effect of stimulation was that there may have been a practice effect, with participants improving in task performance simply because they had experienced the same task before (Donovan and Radosevich, 1999; Fugate, 2007). The design of Experiment 3 accounted for this possibility, finding that there was no effect of practice on any of the tasks that were administered in this experiment.

The results of the meta-analysis and all three experiments are presented in tables 8.1 and 8.2 so that the effects of neuromodulation across all aspects of this thesis can be observed.

Table 8.1. The effects of anodal stimulation on Type 2 processing and executive functions across all four experiments (meta-analysis & three experiments) in this thesis.

Type 2	Meta-Analysis	Exp. 1 (online JDM & offline EF)	Exp. 2 (offline)	Exp. 3 (offline cumul.)		
				Stim vs. sham 1st	Stim vs. sham 2nd	Stim vs. stim
Reflection Left	-	n/a	-	n/a	n/a	n/a
Reflection Right	-	Y	Y	Y	N	Y
Inhibition Left	n/a	-	-	-	-	-
Inhibition Right	n/a	-	-	-	-	-
Updating Left	n/a	-	-	-	-	-
Updating Right	n/a	-	-	-	-	-

All effects are increases in Type 2 cognitive reflection. Abbreviations*:* 'Cumul.' - experiment examining the cumulative effect of stimulation, 'left' – left hemisphere stimulation, 'right' – right hemisphere stimulation, 'JDM' – judgement and decision-making tasks, 'EF' – executive functioning tasks, '-' - no effect of stimulation, 'N/A' - not applicable as this was not tested in this experiment. Under the Experiment 3 heading the experimental conditions and groups are split into: (a) the first experimental groups only for the first sessions ('stim vs. sham 1st'), (b) the second experimental groups only for the second sessions ('stim vs. sham 2nd'), and (c) cumulative stimulation for the repeated stimulation group ('stim vs. stim').

Table 8.2. The effects of anodal stimulation on Type 1 processing across all four experiments (meta-analysis & three experiments) in this thesis.

Type 1	Meta-Analysis	Exp. 1 (online)	Exp. 2 (offline)	Exp. 3 (offline cumul.)		
				Stim vs. sham 1st	Stim vs. sham 2nd	Stim vs. stim
Online Left	Y	n/a	n/a	n/a	n/a	n/a
Online Right	-	N	n/a	n/a	n/a	n/a
Offline Left	-	n/a	-	n/a	n/a	n/a
Offline Right	-	n/a	N	N	Y	Y

All effects are increases in Type 1 processing. Abbreviations*:* 'Cumul.' - experiment examining the cumulative effect of stimulation, 'left' – left hemisphere stimulation, 'right' – right hemisphere stimulation, '-' - no effect of stimulation, 'N/A' - not applicable as this was not tested in this experiment. Under the Experiment 3 heading the experimental conditions and groups are split into: (a) the first experimental groups only for the first sessions ('stim vs. sham 1st'), (b) the second experimental groups only for the second sessions ('stim vs. sham 2nd'), and (c) cumulative stimulation for the repeated stimulation group ('stim vs. stim').

Throughout the experiments in this thesis there were three main themes (i) online stimulation versus offline stimulation effects on Type 1 and Type 2 processing, (ii) the effects of stimulation on executive functioning, and (iii) the effects left hemisphere stimulation versus right hemisphere stimulation on the dual-process framework of judgement and decision-making. All of these themes go some way to answering the aims of this research that were set out in Chapter 1, to examine the neural substrates of judgement and decision-making in the dual-process framework.

In the meta-analysis the effects of online and offline neuromodulation were analysed to reveal that only online stimulation of the left hemisphere modulated decision-making – decreasing Type 1 processing (Table 8.2). Experiment 1 found that online stimulation enhanced cognitive reflection (Type 2) (Tables 8.1 and 8.2). Experiments 2 and 3 found that offline stimulation also increased cognitive reflection (Table 8.1). The effects of online stimulation on judgement and decision-making occur as a result of the task-relevant neuronal populations in the right DLPFC, which are active whilst engaging in decision-making, being enhanced further by the anodal neuromodulation (Aron, Robbins, and Poldrack, 2004; Nitsche et al., 2008). The online stimulation boosts the probability for controlled cognitive reflection (Type 2) to override and correct autonomous intuitive thinking (Type 1). The effects of offline stimulation on decision-making are likely driven be changes in synaptic strength that involve the modulation of glutamatergic activity through the potentiation of synaptic glutamatergic receptors (Nitsche et al., 2003; Stagg & Nitsche, 2011) – however, other yet unknown neurotransmitters may also be involved in this process. Thus, one can conclude that the neuronal population in the right DLPFC are involved in decision-making, and as such are enhanced by anodal stimulation regardless of whether online or offline stimulation is administered (Liebetanz et al., 2002).

As there was an effect of neuromodulation on Type 1 and Type 2 processing this poses the critical question as to why there was no effect of stimulation on any of the executive functioning tasks. The dual-process framework posits that inhibition, updating and set-shifting are crucial to engaging in judgement and decision-making (see Chapter 3) (Stanovich, 2009; Pennycook, Fugelsang, and Koehler, 2015; Friedman and Miyake, 2017). The evidence from neuroimaging and neuromodulation studies also indicate that the right DLPFC is involved in all three executive functions (Rubia et al., 2003; Simmonds, Pekar, and Mostofsky, 2008; Loftus et al., 2015). The evidence for updating primarily comes from experiments that utilise the n-back (Jaeggi et al., 2010; Katsoulaki, Kastrinis, and Tsekoura, 2017) and Sternberg (Gladwin et al., 2012; Hill, Fitzgerald, and Hoy, 2015) tasks. Some of these experiments implicate the involvement of other brain regions suggesting that the right DLPFC is not responsible for updating alone (Hill, Fitzgerald, and Hoy, 2015; Talsma, Kroese, and Slagter, 2017). Whilst many other experiments that target the right DLPFC based on neuroimaging data fail to find an effect of stimulation on updating (Hill, Fitzgerald, and Hoy, 2015; Nikolin et al., 2018). A meta-analysis by Hill and colleagues (2015) questioned the efficacy of neurostimulation for modulating updating. Once the sixteen experiments included in their meta-analysis were analysed there was a small effect size for offline stimulation on working memory and no significant effect for online stimulation. They emphasise that higher current densities and longer stimulation durations might be more effective at modulating working memory performance (Hill, Fitzgerald, and Hoy, 2015). The lack of an effect of stimulation on updating in the experiments in this thesis do not necessarily eliminate the involvement of the right DLPFC in updating.

Another reason may be that the neural substrates of type of inhibition involved in the SST being located in the inferior frontal cortex (IFC) rather than the right DLPFC (Jacobson, Javitt, and Lavidor, 2011; Tian, Ren, and Zang, 2012). Neuromodulation (Jacobson, Javitt, and Lavidor, 2011) and neuroimaging (Tian, Ren, and Zang, 2012) studies have both found that the IFC is active during inhibitory control during the SST performance. In the neuroimaging research functional magnetic resonance imaging (fMRI) has revealed that activity in the IFC increases with the recruitment of response inhibition in the stop signal reaction time trials (Tian, Ren, and Zang, 2012). These neuroimaging results indicate that (i) the type of inhibition involved in cognitive reflection, although similar, is not identical to the inhibition involved in Type 2 processing when overriding Type 1, and (ii) that another inhibition task such as the Go / no go task could detect inhibitory control during decision-making (Swick, Ashley, and Turken, 2011). The Go / no go task was not administered during any of the experiments in this thesis as it was believed at the time of data collection that the inhibition involved in the dual-process framework functions could be captured with the Stroop (Stroop, 1935), AST (Hanania and Smith, 2010), SST (Aron, 2003). The Go / no go could be applied to capture inhibition during decision-making as it is linked to inhibition to the DLPFC (Menon et al., 2001; Simmonds, Pekar, and Mostofsky, 2008). This is supported by a meta-analysis of the fMRI and Go / no go task studies which have revealed that the right DLPFC is involved in response inhibition (Simmonds, Pekar, and Mostofsky, 2008).

A possible further explanation is that whilst response inhibition is crucial to Type 2 processing overriding Type 1 processing, the exact type of inhibition remains unclear – as there is not a single type of inhibition (Rubia et al., 2003; Bari and Robbins, 2013). Efforts were made in this thesis to examine also far inhibition with the AST (Hanania and Smith, 2010) and near inhibition with the SST (Swick, Ashley, and Turken, 2011). As with the updating literature neuromodulation and neuroimaging studies suggest that the right DLPFC is involved in inhibitory control (Simmonds, Pekar, and Mostofsky, 2008; Loftus et al., 2015). Although the right DLPFC is involved in inhibition it is possible that this region acts with interconnected regions such as the IFC (Menon et al., 2001; Aron, Robbins, and Poldrack, 2004) to inhibit pre-potent responses during Type 1 thinking. Evidence for this comes from the many experiments that find that the other regions such as the IFC (Menon et al., 2001; Aron, Robbins, and Poldrack, 2014), orbitofrontal cortex (OFC) (Aron, Robbins, and Poldrack, 2014) and medial prefrontal cortex (MPFC) (Rubia et al., 2003) are active during response inhibition. Secondly, as mentioned previously the inhibition tasks administered during this thesis may not capture the type of inhibition that is crucial to Type 2 processing overriding Type 1. This suggests that if another inhibition task, for example the Go / no go task (Aron, Robbins, and Poldrack, 2004; Swick, Ashley, and Turken, 2011) was administered with higher current densities and longer stimulation durations this might capture inhibitory control during decision-making (Rubia et al., 2003; Bari and Robbins, 2013). As with the updating processes these findings do not necessarily mean that there is no involvement of the right DLPFC in inhibition during judgement and decision-making.

Further to testing the typical CRT (Frederick, 2005; Toplak, West, and Stanovich, 2011), in which mathematical ability is needed to correctly solve the items Experiments 2 and 3 went one step further. Verbal-CRT items that do not have a mathematics element were administered alongside the typical items to reduce the potential reliance on numerical skills (Frederick, 2005; Sirota et al., 2017). Interestingly, neither Experiment 2 nor 3 found an effect of anodal stimulation on the verbal-CRT items despite the increased accuracy for the typical CRT items after stimulation. This was potentially because the CRT's presumed reliance on mathematical ability (Weller et al., 2013; Thomson and Oppenheimer, 2016). However, at the same time, tasks invoking representativeness heuristics showed similar patterns as the typical (numerical) CRT, despite no need for any number-based operations. This pattern of findings suggests that it is not mere numerical processing that is improved after anodal stimulation of the right DLPFC. One explanation for this result could be that typical CRT items prompt cognitive reflection whilst verbal information primes more intuitive level processes (Windschitl & Wells, 1996). A more straightforward explanation could be that success in the verbal CRT was simply less reliant on inhibitory processes but rather relied on linguistic ability. In contrast, the typical CRT may depend more on executive functions that may include impulse control (Loftus et al., 2015) and set-shifting (Tayeb and Lavidor, 2016) – both of which have neural substrates in the right DLPFC (Santarnecchi, Rossi, and Rossi, 2015; Tayeb and Lavidor, 2016), even though as described there was no evidence of these processes here.

For belief bias syllogisms there was no effect of direct current stimulation on the right DLPFC in Experiments 1 or 2. There are a number of possible reasons for this observation. An increase of cortical excitability of the right DLPFC might not influence syllogistic reasoning (as evidenced by the logic index score) because there is no need for inhibition for all task variants, e.g., when logic and beliefs do not conflict (Ball et al., 2006; De Neys and Schaeken, 2007). Furthermore, rather than the DLPFC, the inferior frontal cortex has been increasingly associated with correctly solving syllogisms (Tsujii and Watanabe, 2009; Tsujii et al., 2011). In fact, left DLPFC stimulation in comparison to right DLPFC stimulation reduced overall deductive thinking (indicated by the logic index score) in Experiment 2. This result does fit in general with previous observations that deductive performance with categorical syllogisms seems associated with left frontal brain areas (Goel et al., 2009).

One way in which this thesis went a step further than much of the previous research on the dual-process framework (Haigh, 2016; Szaszi et al., 2017) was to control for thinking dispositions and cognitive characteristics that could interfere with decision-making (Epstein et al., 1996; Haran, Ritov, and Mellers, 2013). Across Experiments 2 and 3 the participants' scores for AOT (Haran, Ritov, and Mellers, 2013), REI (Epstein et al., 1996), BIS (Patton, Stanford, and Barratt, 1995) and NART (Nelson and Willison, 1991) were measured before stimulation. These were recorded because some of the variance in CRT performance can be explained by these thinking dispositions (Campitelli and Labollita, 2010; Stanovich et al., 2009) and cognitive characteristics (Epstein et al., 1996). Likewise, individual differences in Type 2 processing in general have been proposed to reflect differences in thinking dispositions, and not merely abilities in executive function, such as inhibition. For example, individuals who score highly on the AOT scale (Haran, Ritov, and Mellers, 2013) are thought to be open-minded and prone to processing new information. High AOT scores have indeed been positively correlated with performance in the CRT and belief bias syllogistic reasoning (Campitelli and Labollita, 2010). Stanovich's (2009) tripartite model of decision-making contains not only Type 1 and Type 2 processes, but also the reflective mind (i.e., the proclivity to like and engage in reflective thinking will determine the use of one's algorithmic mind, which is the ability to inhibit Type 1 responses) which corresponds to thinking dispositions. Other cognitive models that were covered in the introduction for this thesis contain components for executive functions such as inhibitory control (De Neys' 2012; Handley & Trippas, 2015; Pennycook 2015) but not thinking dispositions or cognitive characteristics. Analyses factoring in these thinking dispositions and cognitive characteristics in Experiments 2 and 3 revealed that the increase in cognitive reflection (Type 2) cannot be explained by any of these controls.

There are at least two alternative explanations for the increase in cognitive reflection (Type 2) after the neuromodulation of the right DLPFC. The first explanation is that although efforts were made to control for thinking dispositions and cognitive characteristics by measuring these prior to stimulation the possibility exists the change in cortical excitability altered these after they were recorded. For example, in the case of the AOT, the analyses found no difference in open-mindedness across any of the experimental conditions and groups (across each of the experiments). However, if open-mindedness was boosted by the neuromodulation then only measuring AOT scores before stimulation would not capture a change in this thinking disposition. Once would need to record AOT scores before and after stimulation to capture a change here. Thus, there is a possibility that the neuromodulation caused a change in thinking disposition, which in turn, increased Type 2 thinking. The second explanation is that an unknown variable could have could have contributed or caused the increase in cognitive reflection after the stimulation of the right DLPFC.

8.2 Research question one: Does neuromodulation of the frontal brain areas affect judgement and decision-making tasks?

Throughout all experiments in this thesis, and the meta-analysis, the results have provided evidence that neuromodulation of the frontal brain areas does affect judgement and decision-making which are purported to rely on the inhibition of pre-potent responses (e.g., the CRT). The meta-analysis started by showing that online stimulation of the left frontal lobe decreases intuitive (Type 1) thinking and reduces risk-taking (Chapter 4). The experimental studies (Chapters 5-7) then provided clear evidence that anodal stimulation of the right DLPFC reduces intuitive (Type 1) thinking whilst increasing cognitive reflection (Type 2). The meta-analysis was limited by the number of publications on decision-making and neuromodulation, many of which solely focused on risk-taking. The presumed mechanisms behind the improved cognitive reflection and Type 2 processing across all of the experiments was that the neural substrates of inhibitory control (Jacobson, Javitt, and Lavidor, 2011; Swick, Ashley, and Turken, 2011) and updating (Hill, Fitzgerald, and Hoy, 2015; Nikolin et al., 2018) a localised to the frontal lobe. As inhibition and updating are crucial components of the dual-process framework (Sloman, 1996; Evans, 2012) it was hypothesised, but not found, that neuromodulation would enhance the capacity for Type 2 processing to override and correct Type 1 processing, thereby increasing the percentage of correct answers on the CRT and representativeness vignettes (Grether, 1980; Frederick, 2005). In short, executive functions may be dissociable from decision-making (Toplak, 2014). Neuromodulation of the frontal lobe does affect judgement and decision-making.

8.3 Research question two: Does stimulating different areas of the prefrontal cortex modulate performance in tasks associated with Type 1 and Type 2 processing differently?

The meta-analysis and three experiments have sought to answer this question with the use of a number of tasks that tap decision-making as conceptualised by the dual-process framework. In all of the experiments Type 1 and Type 2 analyses were conducted to address this question.

The meta-analysis found an effect of left frontal lobe stimulation on Type 1 processing with decreased intuitive responding during online stimulation. Crucially, there was no significant effect of stimulation on Type 2 processing in the meta-analysis for the left frontal lobe. An important point to remember here is that decreasing Type 1 processing is not necessarily the same as increasing Type 2 processing which is why the individual Type 1 and Type 2 analyses were conducted. The left frontal lobe was stimulated in Experiment 2. No effect of stimulation for the left frontal lobe was found for experiment 2 on either Type 1 or Type 2 processing. However, there was an effect of left frontal lobe stimulation for decision-making in which inhibitory control, as conceptualised by the dual-process framework, was not needed (Stupple, Ball, Evans, & Kamal-Smith, 2011; Stupple, Gale, & Richmond, 2013) – as the BBS logic index scores decreased here. This suggests that the left frontal lobe may be involved in decision-making that does not require the successful inhibition of pre-potent responses.

The key findings for the neural substrates of Type 1 and Type 2 processing are provided by the three experiments in this thesis. Across all three experiments right DLPFC stimulation enhanced Type 2 processing whilst there was no change Type 1 processing (after a single session of neuromodulation). This suggests that the right DLPFC is involved in cognitive reflection as stimulating here increases the capacity for the Type 2 processing to override Type 1 processing. Alternatively, the left DLPFC presumably has in a role in Type 1 thinking (albeit this was not evident with anodal stimulation), as Oldrati et al., (2016) found a reduction in Type 1 responding for the CRT after cathodal stimulation.

Table 8.3. The effects of anodal stimulation on the CRT (Type 1 and Type 2) across all three experiments in this thesis after right DLPFC neuromodulation.

	Exp. 1 (online)	**Exp. 2 (offline)**	**Exp. 3 (offline cumul.)**		
			Stim vs. sham 1st	**Stim vs. sham 2nd**	**Stim vs. stim**
Type 1	N	N	N	Y	Y
Type 2	Y	Y	Y	Y	Y

Abbreviations*:* ‘Cumul.’ - experiment examining the cumulative effect of stimulation. Under the Experiment 3 heading the experimental conditions and groups are split into: (a) the first experimental groups only for the first sessions (‘stim vs. sham 1^{st}’), (b) the second experimental groups only for the second sessions (‘stim vs. sham 2^{nd}’), and (c) cumulative stimulation for the repeated stimulation group (‘stim vs. stim’).

8.4 Research question three: What is the relationship between executive functions (e.g., updating, inhibition) and Type 2 thinking performance?

The experiments in this thesis sought to address the relationship between executive functions and Type 2 thinking performance. The numerical Stroop (Stroop, 1935), attention switching task (AST) (Hanania and Smith, 2010) and stop signal task (SST) (Boehler et al., 2010) were all administered to measure inhibition. To measure updating the Sternberg task (Gladwin et al., 2012) and the n-back (2-back and 3-back) (Hill, Fitzgerald, and Hoy, 2015) were administered. None of the studies revealed any significant effects of anodal stimulation on executive functions which went against the predictions. As Type 2 processing overriding Type 1 processing is reliant on the inhibition of the latter it was expected that any effects of stimulation on cognitive reflection (Type 2) would correspond to an increase in inhibition and updating. This was based on the psychological literature (without neuromodulation) which often reports a positive correlation between executive functioning and Type 2 processing – as inhibition and updating increase so does Type 2 processing (Campitelli and Labollita, 2010; Toplak, West, and Stanovich, 2011; Teovanović, Knežević, and Stankov, 2015).

Crucially, although there was no effect of anodal stimulation of the right DLPFC (or left DLPFC) on executive functioning the only increase in Type 2 processing was observed after the stimulation of the right DLPFC. Since neuroimaging and neuromodulation studies report that the right DLPFC is associated with the neural substrates of inhibition (Simmonds, Pekar, and Mostofsky, 2008; Imburgio and Orr, 2018) and updating (Hill, Fitzgerald, and Hoy, 2015; Nikolin et al., 2018) the increase in Type 2 processing infers a relationship between executive functioning and Type 2 processes. As the right DLPFC is stimulated inhibition and updating improves and thereby increases Type 2 processing - bearing in mind that the executive function tasks included in this thesis may have not been sensitive to neurostimulation.

The dual-process framework models explicitly predict a relationship between executive functioning and Type 2 processing (Stanovich, 2009; De Neys, 2012). For example, De Neys' (2012) logical intuition model and Stanovich's tripartite model (2009) both posit that in order for the successful use of Type 2 processing to occur the pre-potent Type 1 process must cease and be overridden by the former.

8.5 Research question four: What is the nature of the interaction between Type 1 and Type 2 processing in the dual-process framework of judgement and decision-making?

The Type 1 and Type 2 analyses in the meta-analysis and all experiments sought to examine the interaction between the processes in the dual-process framework of judgement and decision-making. By using the CRT, which can be answered with responses that are consistent with Type 1 or Type 2 processing it was possible to examine the interaction between these processes. Moreover, executive functioning tasks were used to examine the properties of these dual-processes. Specifically, inhibition was examined with the use of the AST and SST, whilst to investigate updating the n-back (2-back and 3-back) and Sternberg tasks were used.

Crucially, although tasks were administered to capture executive functioning in these experiments there were no effects of stimulation on inhibition or updating in Experiments 1, 2 or 3. However, there were consistent effects of stimulation on the CRT throughout these experiments. Specifically, Type 1 processing was not modulated by a single session of stimulation, whilst conversely, Type 2 processing was – with cognitive reflection increasing in all instances. From these results there is no evidence to support the sequential models of dual-process decision-making (Evans, 1989; Pennycook, Fugelsang, and Koehler, 2015). If Type 1 processing precedes Type 2 processing, as in the sequential models, then there would be a consistent effect of stimulation on both Type 1 and Type 2 processing (there was not). Furthermore, the sequential models specify that when Type 1 processing ends and Type 2 processing begins there is a conflict detection function that inhibits the former in favour of the latter – there was no evidence of inhibition from the executive function tasks (i.e., the AST and SST) in these experiments.

In short, the pattern of results from the experiments within this thesis are more compatible with the hybrid (Strack and Deutsch, 2004; Stanovich, 2009) and parallel (Epstein, 1973; Sloman, 1996) models of dual-process judgement and decision-making as Type 1 and Type 2 processing are not both modulated in the same stimulation conditions / groups. Thus, it is presumed that Type 1 and Type 2 processing may run in parallel, in a 'first-horse-past-the-post' pattern until either process produces a solution to the CRT.

8.6 Study limitation and caveats

There were a few limitations and caveats to the experiments included in thesis. Firstly, bilateral montages were used throughout the three experiments. A bilateral montage was used in the first experiment because this experiment sought to replicate and extend research that had previously used an identical bilateral montage over the right DLPFC and left DLPFCs (Cheng and Lee, 2015). After Experiment 1, Experiment 2 used experimental groups with the anode electrode over the right DLPFC with return electrode over the left DLPFC then in another experimental group the montage was reversed. As there was no effect of stimulation for the anodal left DLPFC group on cognitive reflection (in either direction) the return electrode in the first group did not interfere with the anode over the right DLPFC – thus this bilateral montage was not an issue. Study three then continued to use the same bilateral montage to extend the findings of the first two experiments.

A second potential limitation for the studies in this thesis were the sample sizes that were used in each of these experiments. There were thirty, fifty-four, and forty-eight participants in Experiments 1, 2 and 3 respectively. Although this may appear to be a limitation compared to much of the psychological research which use larger sample sizes neuromodulation research typically use small sample sizes (Hecht, Walsh, and Lavidor, 2010; Hecht, Walsh, and Lavidor, 2013). Power calculations were used to determine sample sizes for each of these experiments. Then slightly larger sample sizes were used to account for participant drop-out rates, participants not following task instructions and problems with the neuromodulation equipment.

The final limitation for the experiments in this thesis were that due to time constraints, and the desire to avoid participant fatigue as a confound, on administering tasks during, or after, anodal stimulation (Fritsch et al., 2010; Bikson et al., 2016) multiple tasks measuring executive functioning were not administered throughout all experiments. None of the tasks that reportedly measure executive functioning (inhibition and updating) detected effects of anodal stimulation over the right DLPFC. It is possible that since some of the neural substrates of executive functioning are located in the right DLPFC, administering the correct task such as the Go / no go may capture an effect of stimulation (Aron, Robbins, and Poldrack, 2004). Although this was a limitation in these experiments efforts were made to measure executive functioning with multiple tasks in the second and third experiments.

8.7 Study strengths

The experiments in this thesis go further than much of the research on cognitive reflection with the CRT in a number of ways (De Neys, Rossi, and Houdé, 2013; Johnson, Tubau, and De Neys, 2016). During the design of these experiments thinking dispositions (Epstein et al., 1996; Haran, Ritov, and Mellers, 2013) and executive functions (Miyake et al., 2000; Friedman and Miyake, 2017) were accounted for. Neuromodulation montages examined the neural correlates of the left frontal lobe and right frontal lobe with online and offline stimulation for the dual-processes. Cognitive reflection was then investigated with items that varied in their mathematical content

(Thomson and Oppenheimer, 2016; Sirota et al., 2017) and at analyses for Type 1 and Type 2 responses (Oldrati et al., 2016).

Experiments 2 and 3 controlled for thinking dispositions (Epstein et al., 1996; Haran, Ritov, and Mellers, 2013) and cognitive ability (Nelson and Willison, 1991). These individual differences are presumed to affect decision-making as they positively correlate with Type 2 processing in many experiments (Toplak, West, and Stanovich, 2011; Teovanović, Knežević, and Stankov, 2015). Furthermore, the reflective mind in Stanovich's tripartite was built into his model account for these individual differences. Thus, unlike the researchers that do not carefully design experiments account for these thinking dispositions and cognitive characteristics these can be eliminated as a source of interference in results.

All of the experiments examined the crucial executive functions for the dual-process framework, namely inhibition and updating (Kiesel et al., 2010; Ren et al., 2017). Set-shifting would have been investigated had a suitable test been available (Miyake et al., 2000). These executive functions were examined alongside Type 1 and Type 2 processing.

Furthermore, the neural correlates of the dual-process framework were examined in the progressive series of experiments in the left frontal lobe (Chapters 4 and 5) and right frontal lobe (Chapters 4 to 7). Examining one side of the frontal lobe alone would leave the question as to whether the contralateral side would produce an opposite pattern of results. By examining the left and right frontal lobes the neural correlates of Type 1 and Type 2 processing were linked to the right DLPFC.

To examine the efficacy of neuromodulation to modify Type 1 and Type 2 processing online (Chapters 4 and 5) and offline (Chapters 4, 6 and 7) stimulation were used throughout these experiments. Typically, neuromodulation experiments only examine the effects of stimulation through the use of only one of these types of stimulation, either online or offline, as they are limited by time (Gorini et al., 2014; Sellaro et al., 2015). The progressive nature of these experiments meant that online and offline neuromodulation could be used across these experiments.

At the task level there were two strengths to the experiments in this thesis. Firstly, critics of the CRT suggest that mathematical ability explains CRT results (Weller et al., 2013; Welsh, Burns, and Delfabbro, 2013). Part of the experimental designs of experiments 2 and 3 sought to investigate these criticisms by using the original CRT, with mathematical elements, and a version of the CRT without any elements of numeracy (Sirota et al., 2017). In doing this this was the first test of the none-mathematical verbal-CRT (Sirota et al., 2017). Secondly, the CRT items and representativeness vignettes were analysed for Type 1 and Type 2 responses. By analysing Type 1 and Type 2 responses rather than just Type 2 responses the nature of the interaction between these processes could be examined as in Oldrati et al., (2016).

8.8 Future research

There are several directions that research could take in the future to build on and extend the findings of the experiments in this thesis. One direction would be to examine either Type 1 or Type 2 processing with neuromodulation and a battery of tasks that measure executive functioning (inhibition, updating and set-shifting (Criaud and Boulinguez, 2013; Nikolin et al., 2018)) in the scope of one of the dual-process framework models. By doing so the relationship between these executive functions and either intuitive Type 1 processing or analytic Type 2 processing could be examined further.

A second direction in which future research could go would be to examine the role of thinking dispositions and cognitive characteristic controls in dual-process decision-making further. For example, by dividing experimental groups into high or low AOT (Haran, Ritov, and Mellers, 2013) before applying the neuromodulation. In this thesis these variables were recorded, but experimental groups were not divided into high versus low groups. By doing this one could determine if the neuromodulation of the right DLFPC interacts and moderates cognitive reflection in high or low thinking disposition scorers differently.

Another direction in which the research could be taken would be to explore the cumulative effects of anodal stimulation that were found in Experiment 3. To-date these cumulative effects of stimulation used in clinical neuroscience for the treatment of depression (Brunoni et al., 2014; Mutz, Edgcumbe, Brunoni, & Fu, 2018) but there are very few examples in the cognitive neuroscience literature (Talsma, Kroese, and

Slagter, 2017; Gilmore et al., 2018). These cumulative effects revealed stepwise increase in cognitive reflection over two sessions of stimulation. More sessions of stimulation could be administered with different tasks or with varying stimulation parameters.

Other directions would be to examine the resting state electroencephalography (EEG) with tasks that capture dual-process thinking and neuromodulation. Or to examine the role of covariates (e.g., religiosity, education etc) in the scope of the dual-process framework.

8.9 Conclusion

The present experiments sought to (i) investigate the neural substrates of judgement and decision-making in the dual-processes framework, (ii) to investigate the sources of variance in Type 2 responding, and (iii) to investigate the relationship between the processes of this framework. Sources of variance in decision-making were explored with measures of thinking dispositions, cognitive characteristics, and executive functions. Throughout the three experiments, and the meta-analysis, these aims were achieved with the use of tDCS neuromodulation. The crucial findings were that anodal neuromodulation of the right DLPFC can increase Type 2 processing whilst decreasing Type 1 responding. These experiments were not the first to explore Type 2 processing with tDCS neuromodulation (Oldrati et al., 2016), but were the first to enhance cognitive reflection (Type 2) with neuromodulation. These were also the first experiments to use a version of the CRT that is not reliant on numeracy alongside the original CRT.

The applied implications of this research, building on these experiments are that tDCS could be used to improve Type 2 thinking individuals with dementia or problem gambling behaviours. In persons with dementia this could improve, or help treat, the symptoms of dementia that make decision-making difficult. Whereas, in problem gamblers the tDCS over the right DLPFC can be used to cognitive reflection so that these individuals are less prone towards problem gambling.

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Appendix A

Heuristics and biases material description

Availability heuristic. The availability heuristic relies on an immediate example that comes to a person's mind. The immediate example must be qualitatively different to another example. For example, when asked *'Are there more hours of rain or sunshine in the United Kingdom?'* one may remember more hours of rain more easily than sunshine.

Framing bias. The framing bias (also called the framing effect) relies on the way in which information is presented. If the information is presented positively then one may consider the information to be positive. For example, when the number of people with (or without) a disease is presented as a loss (i.e., a negative - *200 people out of 500 caught the disease*) or gain (i.e., a positive – *300 people out of 500 did not catch the disease)* one considers the former to be negative, and the latter positive. Crucially, the information is identical in both case with only the way in which the information differing.

Sample size bias. The sample size bias examines one's understanding that a large sample size is more likely to approximate a population value when all other things are equal. For example, after one has been told that there are tennis players and player A is better than player B. Then *'Which player is more likely to win with a 15-point scoring system?'* In this case, the better player (player A) chances of winning would increase with more scoring opportunities.

Sunk cost bias. The sunk cost bias (also called the sunk cost fallacy) relies on the misconception that after one has committed resources to something then one should continue to commit more resources, otherwise the original commitment would go to waste. For example, if a company committed £1 million to developing a new electric car and then electric cars become undesirable one should finish the development by committing the last £500,000 otherwise the original investment would go to waste. Crucially, not committing the second amount of money would be the logical thing to do.

Ratio bias. The ratio bias relies on the preferences of individuals to bet on probabilities that are expressed as a ratio of larger numbers rather than the equivalent probability expressed as a ratio of small numbers. For example, when asked to choose which of the following option one prefers *20:60* or *1:3* the former would be chosen rather than the latter.

Conjunction fallacy. The conjunction fallacy relies on the misconception that a specific condition with two or more properties is more probable than a single condition with only one property. For example, when one is asked *'What is more probable?' (a) Linda is a bank telle*r *and a feminist, or (b) Linda is a bank teller.* The conjunction fallacy incorrectly states that the former is more probable than the latter.

Gambler's fallacy. The gambler's fallacy (also called the Monte Carlo fallacy) relies on the misconception that if something happened more frequently in the past then it is less likely to happen in the future. For example, if a coin is tossed ten times with this coin landing with the tail side up 8 (out of the ten) times then it is more likely to land with the head side up in the future. Crucially, each of the coin throws are independent of each other, there do not influence each other.

Outcome bias. The outcome bias relies on the value given to a decision (i.e., a good or bad decision) when the outcome of the decision is already known. For example, if one were told that a surgical operation was conducted on an individual to correct a life altering medical condition but there were unforeseen complications and the person died one would be likely to conclude that it was a poor decision to operate.

Experiment 1 Stimuli

Note. All stimuli were divided into two equal parts before administering to participants as this was a within-subjects design study. By dividing these items into two equal parts no participants saw the same item twice. For example, the practice syllogism items were divided so that item 1 (*All zookeepers…*) was administered in the first experimental session whilst item 2 (*All Bentleys…*) was seen in the second experimental session. All items were counterbalanced across participants. For example, participant 1 would see part A first then part B, whilst participant 2 would see part B followed by part A. Items were counterbalanced in parts so that the order of items was not the same for all participants. Finally, the different types of items (i.e., representativeness or framing bias) were counterbalanced so that items measuring identical biases (e.g., all framing bias items) did not appear together during testing.

Belief bias syllogisms

Practice items (typical syllogisms)

1. All zookeepers are shoppers. Some pilots are shoppers. Therefore, no pilots are zookeepers. (invalid)

2. All Bentleys are fast. All cars are Bentleys. Therefore, all cars are fast. (valid)

Main items.

Valid-unbelievable

1. No fish can fly. Some dolphins can fly. Therefore, dolphins are fish.

2. All mammals walk. Whales are mammals. Therefore, whales can walk.

3. No cats can swim. Some dog can swim. Therefore, no dogs are cats.

4. All things that are smoked are good for the health. Cigarettes are smoked. Therefore, cigarettes are good for the health.

5. All birds can fly. Penguins cannot fly. Therefore, penguins are not birds.

6. All things that are smoked are good for the health. Cigarettes are smoked. Therefore, cigarettes are good for the health.

7. All animals with four legs are dangerous. Poodles are not dangerous. Therefore, Poodles do not have four legs.

8. All animals love water. Cats do not like water. Therefore, cats are not animals.

Valid-believable

1. No poisons are sold at grocers. Some mushrooms are sold at the grocers. Therefore, some mushrooms are not poisonous.

2. All snakes have scales. Cobras are snakes. Therefore, cobras have scales.

3. All cats have tails. Goldfish do not have tails. Therefore, goldfish are not cats.

4. All felines are curious. Domestic cats are felines. Therefore, domestic cats are curious.

5. No reptiles can grow hair. Some elephants can grow hair. Therefore, no elephants are reptiles.

6. All fizzy drinks are unhealthy. Lemonade is a fizzy drink. Therefore, lemonade is unhealthy.

7. No cigarettes are inexpensive. Some additive things are inexpensive. Therefore, some addictive things are not cigarettes.

8. All birds have feathers. Eagles are birds. Therefore, eagles have feathers.

Invalid-unbelievable

1. All coats made of wool are warm. Ski coats are not made of wool. Therefore, ski coats are not warm.

2. No vegetables contain vitamins. Some vegetables are green foods. Therefore, no green foods have vitamins.

3. All guns are dangerous. Swords are dangerous. Therefore, swords are guns.

4. All athletes are healthy. Darts players are not athletes. Therefore, darts players are not healthy.

5. All sugary foods are healthy. Apples are healthy. Therefore, apples are a sugary food.

6. No unhealthy foods have cholesterol. Some unhealthy foods are fried foods. Therefore, no fried foods have cholesterol.

7. All things made out of wood can be used as fuel. Gasoline is not made out of wood. Therefore, gasoline cannot be used as fuel.

8. All race cars are safe. Motorbikes are safe. Therefore, motorbikes are race cars.

Invalid-believable

1. Some green amphibians are toads. All green amphibians are frogs. Therefore, some frogs are toads.

2. Some pets are cats. All pets are animals. Therefore, some animals are not cats.

3. Some snakes are venomous. All snakes are fast. Therefore, some fast things are venomous.

4. All flowers have petals. Roses have petals. Therefore, roses are flowers.

5. All things that have a motor need oil. Automobiles need oil. Therefore, automobiles have motors.

6. All unemployed people are poor. Bill Gates is not unemployed. Therefore, Bill Gates is not poor.

7. All eastern countries are communist. Canada is not an eastern country. Canada is not communist.

8. Some men are athletes. All men are writers. Therefore, some men are not writers.

Cognitive Reflection Test (6-item version)

Note. Due to programming limitations the CRT was administered on paper in experiment 1. This version of the CRT consisted of Frederick's (2005) and Toplak's (2014) CRT items with the omission of a single item (*A bat and a ball cost £1.10 in total. The bat costs a pound more than the ball. How much does the ball cost?*). The single item was omitted so that the 7-item version consisting of 3 items from Frederick (2015) and 4 items from Toplak (2014) could be evenly divided across the two experimental sessions. This item was chosen as across all 7 items as this item has received extensive publicity (e.g., academic publications, magazines, websites etc), therefore, it was likely that the results of this single item would be unreliable.

Part 1

Please answer the following questions by writing the first answer that comes-to-mind.

a**)** If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets?

………………… minutes.

b) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half the lake?

………………..days.

c) If John can drink one barrel of water in 6 days, and Mary can drink one barrel of water in 12 days, how long would it take them to drink one barrel of water together?

………………….days.

Please put a tick next to any questions that you have seen before.

Part 2

Please answer the following questions by writing the first answer that comes-to-mind.

a**)** Jerry received both the 15th highest and the 15th lowest mark in the class. How many students are in the class?

………………… students.

b) A man buys a pig for £60, sells it for £70, buys it back for £80, and sells it finally for £90. How much has he made?

………………..pounds.

c) Simon decided to invest £8,000 in the stock market one day early in 2008. Six months after he invested, on July 17, the stocks he had purchased were down 50%. Fortunately for Simon, from July 17 to October 17, the stocks he had purchased went up 75%. At this point, Simon has:

a. broken even in the stock market.

b. is ahead of where he began.

c. has lost money.

Please put a tick next to any questions that you have seen before.

Heuristics and biases battery

Practice for heuristics and biases battery

1. In the United States annually which of the following causes more deaths? **(availability)**
   a. Lung cancer
   b. Vehicle accidents

2. In a study 1000 people were tested. Among the participants there were 5 engineers and 995 lawyers. Jack is a randomly chosen participant of this study. Jack is 36 years old. He is not married and is somewhat introverted. He likes to spend his free time reading science fiction and writing computer programmes. **(representativeness)**

   What is most likely?
   a. Jack is an engineer
   b. Jack is a lawyer

3. In the English Language which position is the letter R more likely to appear in? **(availability)**
   a. The first position
   b. The third position

Representativeness items

1. In a study 1000 people were tested. Among the participants there were 4 whose favourite television series is Star Trek and 996 whose favourite series is Eastenders. Jeremy is a randomly chosen participant of this study. Jeremy is 26 and is doing graduate studies in physics. He stays at home most of the time and likes to play video-games.

   What is most likely?

   a. Jeremy's favourite television series is Star Trek

   b. Jeremy's favourite television series is Eastenders

2. In a study 1000 people were tested. Among the participants there were 997 nurses and 3 doctors. Paul is a randomly chosen participant of this study. Paul is 34 years old. He lives in a beautiful home in a posh suburb. He is well spoken and very interested in politics. He invests a lot of time in his career.

   What is most likely?

   a. Paul is a nurse

   b. Paul is a doctor

3. In a study 1000 people were tested. Among the participants there were 990 actresses and 10 librarians. Susan is a randomly chosen participant of this study. Susan is very shy and withdrawn, invariably helpful, but has little interest in people, or in the world of reality. A gentle and tidy soul, she has a need for order and structure and a passion for detail.

   What is most likely?

   a. Susan is an actress

   b. Susan is a librarian

4. In a study 1000 people were tested. Among the participants there were 910 farmers and 90 illustrators. James is a randomly chosen participant of this study. James is meticulous, has a strong eye for detail, enjoys listening to music whilst working and has a creative trait.

   What is most likely?

   a. James is an illustrator

   b. James is a farmer

5. In a study 1000 people were tested. Among the participants there were 4 men and 996 women. Sam is a randomly chosen participant of this study. Sam is 23 years old and is finishing a degree in engineering. On Friday nights, Sam like to go out cruising with friends whilst listening to loud music and drinking beer.

   What is most likely?

   a. Sam is a man

   b. Sam is a woman

6. In a study 1000 people were tested. Among the participants there were 992 musicians and 8 retail managers. Colin is as randomly chosen participant of this study. Colin is a meticulous time keeper, makes notes of everything, keeps a diary, is charismatic and always plans his day ahead.

   What is most likely?

   a. Colin is a musician

   b. Colin is a retail manager

Availability heuristic

1. In the average year in the United Kingdom which of the following are there more hours of?
   a. Rainfall
   b. Sunshine

2. Which of the following countries has the highest number of billionaires?
   a. Turkey
   b. The United Kingdom

3. Which of the following countries has the highest average amount of rainfall?
   a. The United Kingdom
   b. Costa Rica

4. In London annually which of the following groups have more fatalities?
   a. Car drivers
   b. Cyclists

Outcome bias

1. A 55-year-old man had a heart condition. He had to stop working because of chest pain. He enjoyed his work and did not want to stop. His pain also interfered with other things, such as travel and recreation. A type of bypass operation would relieve his pain and increase his life expectancy from age 65 to age 70. However, 8% of the people who have this operation die from the

operation itself. His physicians decided to go ahead with the operation. The operation was a success. Evaluate the physician's decision to go ahead with the operation.

a. 1 = correct

b. 0 = neutral, both opposites are equally good

c. -1 = incorrect

2. A 60-year-old woman had a hip condition. She had to stop working because of the pain. She enjoyed her work and did not want to stop. Her pain also interfered with other things, such as travel and recreation. A type of hip operation would relieve her pain and increase her quality of life. However, 2% of the people who have this operation die from the operation itself. Her physicians decided to go ahead with the operation. The operation was a failure and the patient died. Evaluate the physician's decision to go ahead with the operation.

   a. 1 = correct

   b. 0 – neutral, both opposites are equally good

   c. -1 = incorrect

Framing bias

1. If you were faced with the following choice, which alternative would you choose?

   a. A sure gain of £300

   b. A 75% chance to gain £1300, and 25% chance to gain nothing.

2. If you were faced with the following choice, which alternative would you choose?
    a. A sure gain of £240
    b. A 25% chance to gain £1000, and 75% chance to gain nothing.

3. Imagine that the US is preparing for the outbreak of an unusual disease, which is expected to kill 600 people. Two alternatives programmes to combat the disease have been proposed, which alternative would you choose?
    a. Programme A: 200 people will be saved
    b. Programme B: There is a 1/3 probability that 600 people will be saved, and a 2/3 probability that no people will be saved.

4. Imagine that the US is preparing for the outbreak of an unusual disease, which is expected to kill 600 people. Two alternatives programmes to combat the disease have been proposed, which alternative would you choose?
    a. Programme A: 400 people will die.
    b. Programme B: There is a 1/3 probability that nobody will die, and a 2/3 probability that 600 people will die.

* Framing bias examples adapted from Toplak et al., (2014).

Sunk cost bias

1. Imagine that you have decided to see a play where the admission is £20 per ticket. As you enter the theatre you discover that you have lost a £20 note.

Would you still pay £20 for a ticket for the play?

a. Yes

b. No

2. As a president of an airline company, you have invested £10 million of the company's money into a research project. The purpose was to build a plane that would not be detected by conventional radar, in other words a stealth plane. When the project is 90 percent completed, another company begins marketing a plane that cannot be detected by radar. Also, it is apparent that their plane is much faster and far more economical than the plane that your company is building.

   The question is: Should you invest the last 10 percent of the research funds to finish the stealth plane?

   a. No – It makes no sense to continue spending the money on the project.

   b. Yes – As long as £10 million is already invested, I might as well finish the project.

3. Imagine that you have decided to see a play where the admission is £10 per ticket. As you enter the theatre you discover that you have lost a £10 note. Would you still pay £10 for a ticket for the play?

   a. Yes

   b. No

4. As a president of a supercar company, you have invested £10 million of the company's money into a research project. The purpose was to build an

electric supercar that could perform better than any other supercar. When the project is 90 percent completed, another company begins marketing their electric supercar. Also, it is apparent that their supercar is much faster and far more economical than the car that your company is building.

The question is: Should you invest the last 10 percent of the research funds to finish the electric supercar?

a. No – It makes no sense to continue spending the money on the project.

b. Yes – As long as £10 million is already invested, I might as well finish the project.

Sample size bias

1. A game of squash can be played either 9 or 15 points. Holding all other rules of the game constant, if A is a better player than B, which scoring scheme would give player A a better chance of winning?

   a. 9 points game.

   b. 15 points game.

   c. they are equal

2. A certain town is served by two hospitals. In the larger hospital about 45 babies are born each day, and in the smaller hospital about 15 babies are born each day. As you know, about 50 percent of all babies are boys. However, the exact percentage varies from day to day. Sometimes it may be higher than 50 percent, sometimes lower. For a period of 1 year, each hospital recorded the days on which more than 60 percent of the babies born were boys.

a. The larger hospital

b. The smaller hospital

c. About the same.

Conjunction fallacy

1. Linda is 31 years old, single, outspoken, and very bright. She majored in philosophy. As a student, she was deeply concerned with issues of discrimination. And social justice, and also participated in antinuclear demonstrations.

   Please pick the most likely alternative.

   a. Linda is a bank teller.

   b. Linda is a bank teller and is active in the feminist movement.

2. A health survey was conducted in a representative sample of adult males in London of all ages and occupations. Mr F. was included in the sample. He was selected by chance from the list of participants.

   Which of the following statements is more probable?

   a. Mr F. has had one or more heart attacks.

   b. Mr F. had had one or more heart attacks and he is over 55-years-old.

3. The Scandinavian Peninsula is the European area with the greatest percentage of people with blonde hair and blue eyes. This is the case even though (as in Italy) every possible combination of hair and eye colour occurs. Suppose we choose at random an individual from the Scandinavian population.

Which do you think is the most probable?

a. The individual has blonde hair

b. The individual has blonde hair and blue eyes

4. Professional volleyball players have greatly changed in the course of the last decade. In particular, they have grown younger yet taller. Women players in the first Italian division are on average taller than 1.80 m, ranging between 1.75 m for some setters to more than 1.90 m for many spikers. Suppose we choose at random a female volleyball player from the Italian first division. Which of the following statement is more probable?

   a. The woman is less than 21 years old

   b. The woman is less than 21 years old and is taller than 1.77m

Gambler's fallacy

1. Suppose an unbiased coin is flipped three times, and each time the coin lands on Heads. If you had bet £100 on the next toss, what side would you choose?

   a. Heads

   b. Tails

   c. No preference

2. Suppose an unbiased coin is flipped five times, and each time the coin lands on Tails. If you had bet £100 on the next toss, what side would you choose?

   a. Heads

   b. Tails

   c. No preference

Remote Associative Test (RAT)

Cues	Solution
Cottage/Swiss/Cake	Cheese
Cream/Skate/Water	Ice
Loser/Throat/Spot	Sore
Show/Life/Row	Boat
Night/Wrist/Stop	Watch
Duck/Fold/Dollar	Bill
Rocking/wheel/High	Chair
Dew/Comb/Bee	Honey
Basket/Eight/Snow	Ball
Cadet/Capsule/Ship	Space
River/Note/Account	Bank
Print/Berry/Bird	Blue
Safety/Cushion/Point	Pin
Dream/Break/Light	Day
Fish/Mine/Rush	Gold
High/District/House	School/Court
Sense/Courtesy/Place	Common
Pie/Luck/Belly	Pot
Fox/Man/Peep	Hole
Main/Sweeper/Light	Street
Down/Question/Check	Mark
Master/Toss/Finger	Ring
Hammer/Gear/Hunter	Head
Knife/Light/Pal	Pen
Change/Circuit/Cake	Short
Tail/Water/Flood	Gate
Marshal/Child/Piano	Grand
Cover/Arm/Wear	Under
Rain/Test/Stomach	Acid
Dive/Light/Rocket	Sky
Man/Glue/Star	Super
Tooth/Potato/Heart	Sweet

Appendix B

Experiment 2 Stimuli

Note. As in experiment 1 all items were counterbalanced across participants. The first four of each category of syllogism (e.g., valid-believable) from Appendix A were used for the belief bias syllogisms in experiment 2 – to avoid repetition these do not appear in this appendix.

Cognitive Reflection Test

Note. All CRT items in experiment 2 were administered on a computer. Participants could type any answer on screen. The sources for each CRT item and answers are presented below.

Original CRT (Frederick, 2005)

1. A bat and a ball cost £1.10 in total. The bat costs a pound more than the ball. How much does the ball cost?

   (Intuitive answer 10 pence; correct answer 5 pence).

2. If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets?

   (Intuitive answer 100 minutes; correct answer 5 minutes).

3. In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half the lake?

   (Intuitive answer 24 days; correct answer 47 days).

Toplak (2014).

1. If John can drink one barrel of water in 6 days, and Mary can drink one barrel of water in 12 days, how long would it take them to drink one barrel of water together?
   (Intuitive answer 9; correct answer 4).

2. A man buys a pig for £60, sells it for £70, buys it back for £80, and sells it finally for £90. How much has he made?
   (Intuitive answer £10; correct answer £20).

3. Simon decided to invest £8,000 in the stock market one day early in 2008. Six months after he invested, on July 17, the stocks he had purchased were down 50%. Fortunately for Simon, from July 17 to October 17, the stocks he had purchased went up 75%. At this point, Simon has:
   a. broken even in the stock market.
   b. is ahead of where he began.
   c. has lost money.
   (Intuitive answer b; correct answer c value is £7000).

4. Jerry received both the 15^{th} highest and the 15^{th} lowest mark in the class. How many students are in the class?
   (Intuitive answer 30; correct answer 29).

Thomson & Oppenheimer (2016)

1. If you're running a race and you pass the person in second place, what place are you in?

   (Intuitive answer 1st; correct answer 2nd).

2. A farmer had 15 sheep and all but 8 died. How many are left?

   (Intuitive answer 7; correct answer 8).

3. Emily's father had three daughters. The first two are named April and May. What is the third daughter's name?

   (Intuitive answer June; correct answer Emily).

4. How many cubic feet of dirt are there in a hole that 3' deep x 3' wide x 3' long?

   (Intuitive answer 27; correct answer none/no dirt).

Verbal CRT (Sirota, 2017)

1. How many animals of each sex did Moses take on the ark?

   (Intuitive answer 2; correct answer None, according to mythology Noah did).

2. A monkey, a squirrel, and a bird are racing to the top of a coconut tree. Who will get the banana first, the monkey, the squirrel, or the bird?

   (Intuitive answer monkey or bird; correct answer none, it is a coconut tree).

3. In a one-story pink house, there was a pink person, a pink cat, a pink fish, a pink computer, a pink chair, a pink table, a pink telephone, a pink shower - everything was pink! What colour were the stairs probably?
   (Intuitive answer pink; correct answer there are no stairs).

4. The wind blows west. An electric train runs east. In which cardinal direction does the smoke from the locomotive blow?
   (Intuitive answer east or west; correct answer there is not smoke it is an electric train).

5. If you have only one match and you walk into a dark room where there is an oil lamp, a newspaper and wood - which thing would you light first?
   (Intuitive answer the lamp; correct answer the match)

6. It's a stormy night and a plane takes off from JFK airport in New York. The storm worsens, and the plane crashes - half lands in the United States, the other half lands in Canada. In which country do you bury the survivors?
   (Intuitive answer the United States or Canada; correct answer they are survivors, you don’t bury them).

7. Would it be ethical for a man to marry the sister of his widow?
   (Intuitive answer yes or no; correct answer he cannot he is dead)

8. Which sentence is correct: a) “the yolk of the egg are white” or b) “the yolk of the egg is white”?

(Intuitive answer b; correct answer neither).

Other (to boost power)

1. A clerk in the butcher shop is 5' 10'' tall. What does he weigh?

   (Intuitive answer I don't know; correct answer meat).

Representativeness items

Practice item

1. One thousand people were tested. Among the participants there were 997 girls and 3 boys. Erin is a participant of this study. Erin is 13 years old. Erin's favourite subject is art. Erin's favourite things to do are shopping and having sleepovers with friends to gossip about other children at school.

What is most likely?

a. Erin is a girl.

b. Erin is a boy.

Main items

1. Among a sample of 900 people there were 810 farmers and 90 illustrators. James is a randomly chosen participant. James is meticulous, has a strong eye for detail, enjoys listening to music whilst working and has a creative trait.

What is most likely?

a. James is an illustrator.

b. James is a farmer.

2. At the supermarket there were 600 people. Among the shoppers there were 570 actresses and 30 librarians. Susan is a randomly chosen person from the supermarket. Susan is very shy and withdrawn, invariably helpful, but has little interest in people, or in the world of reality. A gentle and tidy soul, she has a need for order and structure and a passion for detail.

What is most likely?

a. Susan is an actress.

b. Susan is a librarian.

3. In a study 1000 people were tested. Among the participants there were 992 musicians and 8 retail managers. Colin is as randomly chosen participant of this study. Colin is a meticulous time keeper, makes notes of everything, keeps a diary, is charismatic and always plans his day ahead.

What is most likely?

a. Colin is a musician.

b. Colin is a retail manager.

4. A survey of 1500 people was conducted. Among the participants in the survey there were 11 sixteen-year olds and 1489 fifty-year olds. Ellen is a randomly chosen participant of this survey. Ellen likes to listen to hip hop and rap music. She enjoys wearing tight shirts and jeans. She’s fond of dancing and has a small nose piercing.

What is most likely?

a. Ellen is sixteen years old.

b. Ellen is fifty years old.

5. In a study 1000 people were tested. Among the participants there were 4 whose favourite television series is Star Trek and 996 whose favourite series is Eastenders. Jeremy is a randomly chosen participant of this study. Jeremy is 26 and is doing graduate studies in physics. He stays at home most of the time and likes to play video-games.

What is most likely?

a. Jeremy’s favourite television series is Star Trek

b. Jeremy’s favourite television series is Eastenders.

6. In a study of 1000 people there were 5 engineers and 995 lawyers. Jack is a randomly chosen participant of this study. Jack is 36 years old. He is not married and is somewhat introverted. He likes to spend his free time reading science fiction and writing computer programmes.

What is most likely?

a. Jack is an engineer.

b. Jack is a lawyer.

7. 1200 people were tested. Among the participants there were three who live in a condo and 1197 who live in a farmhouse. Kurt is a randomly chosen participant of this study. Kurt works in Canary Wharf and is single. He works long hours and wears Amani suits to work. He likes wearing shades.

What is most likely?

a. Kurt lives in a condo.

b. Kurt lives in a farmhouse.

8. In a nightclub there are 700 people. Among the clubbers there were 4 men and 696 women. Sam is a randomly chosen person from this nightclub. Sam is 23 years old and is finishing a degree in engineering. On Friday nights, Sam like to go out cruising with friends whilst listening to loud music and drinking beer.

What is most likely?

a. Sam is a man.

b. Sam is a woman.

9. Paul is at a large gathering of people. There are 2000 people at his gathering consisting of 1830 nurses and 170 doctors. Paul is a randomly chosen person from this group. Paul is 34 years old. He lives in a beautiful home in a posh suburb. He is well spoken and very interested in politics. He invests a lot of time in his career.

What is most likely?

a. Paul is a nurse.

b. Paul is a doctor.

10. In a shopping centre there were 1600 people. Among the people in the shopping centre there were 1595 who buy their clothes in Primark and 5 who buy their clothes at high-end retailers. Karen is a 33-year-old female. She works in a business office and drives a Porsche. She lives in a fancy penthouse with her boyfriend.

What is most likely?

a. Karen buys her clothes at a high-end retailer.

b. Karen buys her clothes at Primark.

* All representativeness items adapted from De Neys & Glumicic (2008) or Toplak (2014).

Scales and questionnaires administered to record thinking dispositions and cognitive ability.

Note. All of the following scales and questionnaires were administered on paper.

Rational Experiential Inventory – 10 item (REI) (Epstein, 1973).

Below are 10 statements please rate these from 1 to 5 using the following scale. Please write your answer in the space provided near the statement.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1	2	3	4	5

1. I don't like to have to do a lot of thinking_________

2. I try to avoid situations that require thinking in depth about something___________

3. I prefer to do something that challenges my thinking abilities rather than something that requires little thought__________

4. I prefer complex to simple problems_________

5. Thinking hard and for a long time about something gives me little satisfaction__________

6. I trust my initial feelings about people__________

7. I believe in trusting my hunches_________

8. My initial impressions of people are almost always right__________

9. When it comes to trusting people, I can usually rely on my "gut feeling"________

10. I can usually feel when a person is right or wrong even if I can't explain how I know________

Actively Open-Minded Thinking (AOT) scale (Stanovich & West, 2007)

Please read the following instructions carefully, they differ from the instructions in part

Please rate your agreement or disagreement with each statement on a 1 to 7 scale, when 1 = Completely Disagree, 4 = Neutral, and 7 = Completely Agree.

1. Allowing oneself to be convinced by an opposing argument is a sign of good character.

……………..

2. People should take into consideration evidence that goes against their beliefs.

…………..

3. People should revise their beliefs in response to new information or evidence.

…………….

4. Changing your mind is a sign of weakness.

……………..

5. Intuition is the best guide in making decisions.

……………

6. It is important to persevere in your beliefs even when evidence is brought to bear against them. ……………..

7. One should disregard evidence that conflicts with one's established beliefs. …………….

National Adult Reading Test (NART) (Nelson, 1982).

Word Card

CHORD

SUPERFLUOUS

ACHE

SIMILE

DEPOT

BANAL

AISLE

QUADRUPED

BOUQUET

CELLIST

PSALM

FACADE

CAPON

ZEALOT

DENY

DRACHM

NAUSEA

AEON

DEBT

PLACEBO

COURTEOUS

ABSTEMIOUS

RAREFY

DETENTE

EQUIVOCAL

IDYLL

NAIVE

PUERPERAL

CATACOMB

AVER

GAOLED

GAUCHE

THYME

TOPIARY

HEIR

LEVIATHAN

RADIX

BEATIFY

ASSIGNATE

PRELATE

HIATUS

SIDEREAL

SUBTLE

DEMESNE

PROCREATE

SYNCOPE

GIST

LABILE

GOUGE

CAMPANILE

Appendix C

Experiment 3 Stimuli

Note. As in experiments 1 and 2 all items were counterbalanced across participants. The REI, AOT and NART were administered in experiment 3 – to avoid repetition these are not presented below.

Cognitive Reflection Test

Note. The CRT items administered in experiment 3 were divided into two parts for use across the two experimental sessions. All items were counterbalanced as in experiments 1 and 2. All items were presented on a computer as in experiment 2. Each participant received an equal number of verbal CRT items and numeracy-based CRT items per part. The sources of each item is presented below with the intuitive and correct answers.

Part 1

Verbal CRT (Sirota, 2017)

1. How many animals of each sex did Moses take on the ark?
   (Intuitive answer 2; correct answer None, according to mythology Noah did).

2. A monkey, a squirrel, and a bird are racing to the top of a coconut tree. Who will get the banana first, the monkey, the squirrel, or the bird?
   (Intuitive answer monkey or bird; correct answer none, it is a coconut tree).

3. In a one-story pink house, there was a pink person, a pink cat, a pink fish, a pink computer, a pink chair, a pink table, a pink telephone, a pink shower - everything was pink! What colour were the stairs probably?
   (Intuitive answer pink; correct answer there are no stairs).

4. The wind blows west. An electric train runs east. In which cardinal direction does the smoke from the locomotive blow?
   (Intuitive answer east or west; correct answer there is not smoke it is an electric train).

2016 CRT (Thomson & Oppenheimer, 2016)

5. If you're running a race and you pass the person in second place, what place are you in?
   (Intuitive answer 1st; correct answer 2nd).

6. A farmer had 15 sheep and all but 8 died. How many are left?
   (Intuitive answer 7; correct answer 8).

Original CRT (Frederick, 2005)

7. A bat and a ball cost £1.10 in total. The bat costs a pound more than the ball. How much does the ball cost?
   (Intuitive answer 10 pence; correct answer 5 pence).

Tremoliere & De Neys (2014)

8. A Ferrari and a Ford together cost £190,000. The Ferrari costs £100,000 more than the Ford. How much does the Ford cost?
   (Intuitive answer $90,000: correct answer $45,000)

Toplak (2014)

9. If John can drink one barrel of water in 6 days, and Mary can drink one barrel of water in 12 days, how long would it take them to drink one barrel of water together?

   (Intuitive answer 9; correct answer 4).

10. A man buys a pig for £60, sells it for £70, buys it back for £80, and sells it finally for £90. How much has he made?

    (Intuitive answer £10; correct answer £20).

Primi et al., (2015)

11. If three elves can wrap three toys in an hour, how many elves are needed to wrap six toys in 2 hours?

    (Intuitive answer 6 elves: correct answer 3 elves)

Ackerman (2014)

12. A frog fell into a hole 30 meters deep. Every day it climbs up 3m, but during the night it slides 2m back down. How many days will it take the frog to climb out of the hole?

    (Intuitive answer 30 days; correct answer 28 days)

13. Apple mash is comprised of 99% water and 1% apple solids. I left 100 kg mash in the sun and some of the water evaporated. Now the water is 98% of the mash. What is the mash weight?

    (Intuitive answer 99; correct answer 50)

14. If a test to detect a disease whose prevalence is 1/1000 has a false positive rate of 5% what is the chance that a person found to have a positive result actually has the disease, assuming that you know nothing about the person's signs or symptoms?

    (Intuitive answer 95; correct answer 2)

Szaszi et al (2017)

15. There is a running race among A, B, C D, E, F. If B passes the person in second place, what place is B now in.

    (Intuitive answer A: correct answer B)

16. In which decade did the Beatles become the most popular American band ever?

    (Intuitive answer 1960s: correct answer they were not American)

Part 2

Verbal CRT (Sirota, 2017)

1. If you have only one match and you walk into a dark room where there is an oil lamp, a newspaper and wood - which thing would you light first?

   (Intuitive answer the lamp; correct answer the match)

2. It's a stormy night and a plane takes off from JFK airport in New York. The storm worsens, and the plane crashes - half lands in the United States, the other half lands in Canada. In which country do you bury the survivors?

(Intuitive answer the United States or Canada; correct answer they are survivors, you don't bury them).

3. Would it be ethical for a man to marry the sister of his widow?

   (Intuitive answer yes or no; correct answer he cannot he is dead)

4. Which sentence is correct: a) "the yolk of the egg are white" or b) "the yolk of the egg is white"?

   (Intuitive answer b; correct answer neither).

Thomson & Oppenheimer (2016)

5. Emily's father had three daughters. The first two are named April and May. What is the third daughter's name?

   (Intuitive answer June; correct answer Emily).

6. How many cubic feet of dirt are there in a hole that 3' deep x 3' wide x 3' long?

   (Intuitive answer 27; correct answer none – no dirt).

Original CRT (Frederick, 2005)

7. If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets?

   (Intuitive answer 100 minutes; correct answer 5 minutes).

8. In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half the lake?

(Intuitive answer 24 days; correct answer 47 days).

Toplak (2014)

9. Simon decided to invest £8,000 in the stock market one day early in 2008. Six months after he invested, on July 17, the stocks he had purchased were down 50%. Fortunately for Simon, from July 17 to October 17, the stocks he had purchased went up 75%. At this point, Simon has:

   a. broken even in the stock market.

   b. is ahead of where he began.

   c. has lost money.

   (Intuitive answer b; correct answer c value is £7000).

10. Jerry received both the 15th highest and the 15th lowest mark in the class. How many students are in the class?

    (Intuitive answer 30; correct answer 29).

Primi et al., (2015)

11. In an athletics team, tall members are three times more likely to win a medal than short members. This year the team had won 60 medals so far. How many of these have been won by short athletes?

    (Intuitive answer 20 medals; correct answer 15 medals)

Ackerman (2014)

12. Every day, a bakery sells 400 cookies. When the manager is not there, 20% of the cookies made that day are eaten by the staff. How many additional cookies should be made on the manager’s day off to ensure that 400 cookies can be sold?

(Intuitive answers 80, 500; correct answers 100)

13. Steve was standing in a long line. To amuse himself he counted the people waiting, and saw that he stood 38th from the beginning and 56th from the end of the line. How many people are stood in the line?
(Intuitive answers 94 or 92; correct answers 93)

14. Ants are walking in a line. A bad-mannered ant cuts in front of the ant walking second. What is the rude ant's place in the line?
(Intuitive answer 1st; correct answers 2nd)

Szaszi et al (2017)

15. In which day of September did the Twin Towers in Washington DC get attacked by Islamist terrorists?
(Intuitive answer 11th: correct answer The twin towers were in New York not Washington)

16. A plane was flying from Germany to Barcelona. On the last leg of the journey, it developed engine trouble. Over the Pyrenees, the pilot started to lose control. The plane eventually crashed right on the border. Wreckage was equally strewn in France and Spain. Where should the survivors be buried?
(Intuitive answer France or Spain; correct answer neither, they are living – don't bury them)

Representativeness and base-rate items

Part 1

Incongruent vignettes (i.e., representativeness)

1. Among a sample of 900 people there were 810 farmers and 90 illustrators. James is a randomly chosen participant. James is meticulous, has a strong eye for detail, enjoys listening to music whilst working and has a creative trait.

What is most likely?

a. James is an illustrator.

b. James is a farmer.

2. At the supermarket there were 600 people. Among the shoppers there were 570 actresses and 30 librarians. Susan is a randomly chosen person from the supermarket. Susan is very shy and withdrawn, invariably helpful, but has little interest in people, or in the world of reality. A gentle and tidy soul, she has a need for order and structure and a passion for detail.

What is most likely?

a. Susan is an actress.

b. Susan is a librarian.

3. In a study 1000 people were tested. Among the participants there were 992 musicians and 8 retail managers. Colin is as randomly chosen participant of this

study. Colin is a meticulous time keeper, makes notes of everything, keeps a diary, is charismatic and always plans his day ahead.

What is most likely?

a. Colin is a musician.

b. Colin is a retail manager.

4. A survey of 1500 people was conducted. Among the participants in the survey there were 11 sixteen-year olds and 1489 fifty-year olds. Ellen is a randomly chosen participant of this survey. Ellen likes to listen to hip hop and rap music. She enjoys wearing tight shirts and jeans. She’s fond of dancing and has a small nose piercing.

What is most likely?

a. Ellen is sixteen years old.

b. Ellen is fifty years old.

5. In a study 1000 people were tested. Among the participants there were 4 whose favourite television series is Star Trek and 996 whose favourite series is Eastenders. Jeremy is a randomly chosen participant of this study. Jeremy is 26 and is doing graduate studies in physics. He stays at home most of the time and likes to play video-games.

What is most likely?

a. Jeremy’s favourite television series is Star Trek

b. Jeremy’s favourite television series is Eastenders.

6. In a study of 1000 people there were 5 engineers and 995 lawyers. Jack is a randomly chosen participant of this study. Jack is 36 years old. He is not married and is somewhat introverted. He likes to spend his free time reading science fiction and writing computer programmes.

What is most likely?

a. Jack is an engineer.

b. Jack is a lawyer.

7. 1200 people were tested. Among the participants there were three who live in a condo and 1197 who live in a farmhouse. Kurt is a randomly chosen participant of this study. Kurt works in Canary Wharf and is single. He works long hours and wears Amani suits to work. He likes wearing shades.

What is most likely?

a. Kurt lives in a condo.

b. Kurt lives in a farmhouse.

8. In a nightclub there are 700 people. Among the clubbers there were 4 men and 696 women. Sam is a randomly chosen person from this nightclub. Sam is 23 years old and is finishing a degree in engineering. On Friday nights, Sam like to go out cruising with friends whilst listening to loud music and drinking beer.

What is most likely?

a. Sam is a man.

b. Sam is a woman.

9. In a shopping centre there were 1600 people. Among the people in the shopping centre there were 1595 who buy their clothes in Primark and 5 who buy their clothes at high-end retailers. Karen is a 33-year-old female. She works in a business office and drives a Porsche. She lives in a fancy penthouse with her boyfriend.

What is most likely?

a. Karen buys her clothes at a high-end retailer.

b. Karen buys her clothes at Primark.

Congruent base-rate vignettes

1. In a study, 1000 people were tested. Among the participants there were 997 who have a tattoo and 3 without a tattoo. Jay is a randomly chosen participant of this study. Jay is a 29-year-old male. He has served a short time in prison. He has been living on his own for 2 years now. He has an older car and listens to punk music.

What is most likely?

a. Jay has a tattoo.

b. Jay has no tattoo.

2. In a study of 1000 people there were 4 executive managers and 996 kindergarten teachers. Lilly is a randomly chosen participant of this study. Lilly is 37 years old. She is married and has 3 children. Her husband is a veterinarian. She is committed to her family and always watcher the daily cartoon shows with her children.

What is most likely?

a. Lilly is a kindergarten teacher

b. Lilly is an executive manager

3. In a study of 700 people there were 615 television reporters and 85 builders. Ray is a randomly chosen participant of this study. Ray always dresses smartly, liking to wear a suit. He keeps up-to-date with current affairs and speaks very clearly.

What is most likely?

a. Ray is a builder.

b. Ray is a television reporter.

4. In a study of 650 people there were 550 estate agents and 100 professional football players. Donald is a randomly chosen participant of this study. Donald travels a lot for work by car, spends a lot of time on the phone and keeps detailed diary.

What is most likely?

a. Donald is a professional football player.

b. Donald is an estate agent.

5. In a study of 700 people there were 580 concert stage hands and 120 lawyers. Karl is a randomly chosen participant of this study. Karl enjoys player the guitar and listening to music in his spare time. He goes to as many concerts as he can.

What is most likely?

a. Karl is a lawyer.

b. Karl is a concert stage hand.

Neutral base-rate vignettes

1. In a study of 1000 people there were 996 men and 4 women. Casey is a randomly chosen participant of this study. Casey is a 36-year-old writer. Casey has two brothers and one sister. Casey likes running and watching a good movie.

What is most likely?

a. Casey is a man.

b. Casey is a woman.

2. In a study of 1000 people there were 997 people who played the drums and 3 who played the saxophone. Tom is a randomly chosen participants in this study. Tom is 20-years-old. He is studying in Washington and has no steady girlfriend. He just brought a second-hand car with his savings.

What is most likely?

a. Tom plays the drums.

b. Tom plays the saxophone.

3. In a study of 1000 people there were 997 pool players and 3 basketball players. Jason is a randomly chosen participant in this study. Jason is 29-years-old and has lived his whole life in New York. He has green coloured eyes and black hair. He drives a light-grey coloured car.

What is most likely?

a. Jason is a pool player.

b. Jason is a basketball player.

4. In a study there were 1000 participants. Among the participants there were 4 who lived in New York and 996 who lived in Los Angeles. Christopher is a randomly chosen participant of this study. Christopher is 28-years-old. He had a girlfriend and shares an apartment with a friend. He likes watching basketball.

What is most likely?

a. Christopher lives in New York.

b. Christopher lives in Los Angeles.

5. In a study of 1000 people there were 5 computer science majors and 995 English majors. Matt is a randomly chosen participants of this study. Matt is 20-years-old and

lives in downtown Toronto. Matt's favourite food is pasta with meatballs. His parents are living in Vancouver.

What is most likely?

a. Matt is a computer science major.

b. Matt is an English major.

Part 2

Incongruent vignettes (ie., representativeness)

1. In a study, 1000 people were tested. Among the participants there were 3 who have a tattoo and 997 without a tattoo. Jay is a randomly chosen participant of this study. Jay is a 29-year-old male. He has served a short time in prison. He has been living on his own for 2 years now. He has an older car and listens to punk music.

What is most likely?

a. Jay has a tattoo.

b. Jay has no tattoo.

2. In a study of 1000 people there were 996 executive managers and 4 kindergarten teachers. Lilly is a randomly chosen participant of this study. Lilly is 37 years old. She is married and has 3 children. Her husband is a veterinarian. She is committed to her family and always watcher the daily cartoon shows with her children.

What is most likely?

a. Lilly is a kindergarten teacher

b. Lilly is an executive manager

3. In a study of 1000 people there were 996 Bruce Springsteen fans and 4 Britany Spears fans. Tare was randomly chosen for this study. Tara is 15. She loves to go shopping at the mall and to talk with her friends about their crushes at school.

What is most likely?

a. Tara is a Bruce Springsteen fan.

b. Tara is a Britany Spears fan.

4. In a study there were 1000 people, there were 995 Americans and 5 French people. Martine is a randomly chosen participant of this study. Martine is 26-years-old. She is bilingual and reads a lot in her spare time. She is a very fashionable dresser and a great cook.

What is most likely?

a. Martine is American.

b. Martine is French.

5. In a study of 1000 people there were 100 Italians and 900 Swedish participants. Marco has been selected at random for the study. Marco is 16-years-old. He loves to play football with his friends, after which they go out for pizza or to someone's house for homemade pizza.

What is most likely?

a. Marco is Italian.

b. Marco is Swedish.

6. In a study there were 1000 people in a room. There were 900 forty-year old participants and 100 seventeen-year old participants. Ryan is a randomly selected participant of this study. Ryan lives in Guildford. He hangs out with his buddies every day and likes watching MTV. He is a big fan of Green Day and is saving to buy his own car.

What is most likely?

a. Ryan is 40-years-old.

b. Ryan is 17-years-old.

7. In a study there were 1000 people. There were 150 architects and 850 taxi drivers. Steven is a randomly chosen participants of this study. Steven is very shy and withdrawn, invariably helpful, but with little interest in people, or in the world of reality. A meek and tidy soul, he had a need for order and structure, and a passion for detail.

What is most likely?

a. Steven is an architect.

b. Steven is a taxi driver.

8. In a university there were 1000 people. There 175 students of beauty therapy and 825 students of chemistry. Sarah is a randomly selected student from the 1000 people. Sarah loves to listen to new age music and faithfully reads her horoscope each day. In her spare time, she enjoys aromatherapy and attending a local spirituality group.

What is most likely?

a. Sarah is a student of beauty therapy.

b. Sarah is a student of chemistry.

9. In a group there are 800 people. There are 640 social science students and 160 engineering students. Tom was randomly selected from this group. Tom is highly intelligent, although lacking in true creativity. He has a need for order and clarity, and for neat and tidy systems in which every detail finds its appropriate place. His writing is rather dull and mechanical.

What is most likely?

a. Tom is a student of engineering.

b. Tom is a student of social science.

10. In study of 1000 people were tested. Among the participants there were 992 musicians and 8 retail managers. David is as randomly chosen participant of this study. David is a meticulous time keeper, makes notes of everything, keeps a diary, is charismatic and always plans his day ahead.

What is most likely?

a. David is a musician.

b. David is a retail manager.

Congruent vignettes

1. In a study there were 800 people. There were 610 soldiers and 190 doctors. Robert is a randomly chosen participant in this study. Robert spends a lot of time in the gym, travels a lot and takes pride in his physical fitness.

What is most likely?

a. Robert is a soldier.

b. Robert is a doctor.

2. In a study of 650 people there were 600 business owners and 50 taxi drivers. Daisy is a randomly chosen participant in this study. Daisy spends a lot of her time in meetings, updating spreadsheets and on the phone.

What is most likely?

a. Daisy is a business owner.

b. Daisy is a taxi driver.

3. In a study of 900 people there were 750 history students and 150 physical education students. Jenny is a randomly chosen participant in this study. Jenny

spends most of her time reading. She enjoys travelling to National Trust sites and attends historical re-enactments.

What is most likely?

a. Jenny is a history student.

b. Jenny is a physical education student.

4. In a study of 850 participants there were 820 illustrators and 30 barristers. Grant is a randomly chosen participant of this study. Grant reads a lot of comic books, watches super hero films and attends comic con.

What is most likely?

a. Grant is a barrister.

b. Grant is an illustrator.

5. In a study of 1000 people there were 4 executive managers and 996 kindergarten teachers. Sandy is a randomly chosen participant of this study. Sandy is 37-years-old. She is married and has 3 children. Her husband is a veterinarian. She is committed to her family and always watcher the daily cartoon shows with her children.

What is most likely?

a. Sandy is a kindergarten teacher

b. Sandy is an executive manager

Neutral vignettes

1. In a study of 1000 people there were 250 engineers and 750 lawyers. Richard was randomly chosen for this study. Richard is a 30-year-old man. He is married with no children. A man of high ability and high motivations, he promises to be quite successful in his field. He is well liked by his colleagues.

What is most likely?

a. Richard is an engineer.

b. Richard is a lawyer.

2. In a study of 800 people there were 650 scientists and 150 builders. Alvin was randomly chosen for this study. Alvin is 19-years-old and lives in London. Alvin's favourite food is pizza. His parents live in Kent.

What is most likely?

a. Alvin is a scientist.

b. Alvin is a builder.

3. In a study of 900 people there were 750 pilots and 150 cashiers. May is a randomly chosen participant in this study. May is 31-years-old and has lived his whole life in Devon. He has green coloured eyes and black hair. He drives a light-grey coloured car.

What is most likely?

a. May is a pilot.

b. May is a cashier.

4. In a study of 900 people there were 896 men and 4 women. Bobby is a randomly chosen participant of this study. Bobby is a 36-year-old writer. Bobby has two brothers and one sister. bobby likes running and watching a good movie.

What is most likely?

a. Bobby is a man.

b. Bobby is a woman.

5. In a study of 600 people there were 597 people who played the piano and 3 who played the violin. Charlie is a randomly chosen participants in this study. Charlie is 29-years-old. He is studying in Oxford and has no steady girlfriend. He just brought a second-hand car with his savings.

What is most likely?

a. Charlie plays the violin.

b. Charlie plays the piano.

Barratt Impulsiveness Scale (BIS)

Please read the following instructions carefully.

This is a test to measure some of the ways you act and think. Read each statement and indicate on the scale from 1 to 4 the appropriate answer.

1 = Rarely/Never, 2 = Occasionally, 3 = Often, and 4 = Almost always/always.

1. I plan tasks carefully…..

2. I do things without thinking…

3. I make-up my mind quickly…

4. I am happy-go-lucky…

5. I don't "pay attention."…

6. I have "racing" thoughts…

7. I plan trips well ahead of time….

8. I am self-controlled….

9. I concentrate easily…

10. I save regularly…

11. I "squirm" at plays or lectures….

12. I am a careful thinker….

13. I plan for job security….

14. I say things without thinking…

15. I like to think about complex problems…

16. I change jobs…

17. I act “on impulse”….

18. I get easily bored when soling thought problems….

19. I act on the spur of the moment….

20 I am a steady thinker…

21. I change residences….

22. I buy things on impulse….

23. I can only think about one thing at a time….

24. I change hobbies….

25. I spend of charge more than I earn….

26. I often have extraneous thoughts when thinking….

27. I am more interested in the present than the future….

28. I am restless at the theatre of lectures….

29. I like puzzles….

30. I am future oriented….

Appendix D

Ethical Approval letters

Experiments 1 and 2

Amendment reference number: AMD 1617 12

UREC reference number: UREC 1516 67

Experiment 3

UREC reference number: UREC 1718 11

06th October 2016

Dear Daniel,

Project Title:	**Human reasoning and decision-making: How do we make decisions intuitively and how do these decisions interact with system 2 process our decisions?**
Researcher:	**Daniel Edgcumbe**
Principal Investigator:	**Dr Volker Thoma**
Amendment reference number:	**AMD 1617 12**
UREC reference no of original approved application:	**UREC 1516 67**

I am writing to confirm that the application for an amendment to the aforementioned research study has now received ethical approval on behalf of University Research Ethics Committee (UREC).

Should you wish to make any further changes in connection with your research project, this must be reported immediately to UREC. A Notification of Amendment form should be submitted for approval, accompanied by any additional or amended documents: http://www.uel.ac.uk/wwwmedia/schools/graduate/documents/Notification-of-Amendment-to-Approved-Ethics-App-150115.doc

Approved Research Site

I am pleased to confirm that the approval of the proposed research applies to the following research site:

Research Site	Principal Investigator / Local Collaborator
University of East London premises	Dr Volker Thoma

Summary of Amendments
The planned amendments regard changes to the second study in the original ethics form. The procedure will be changed and some of the tasks will reduced (fewer tasks). Two additional questionnaires (The Rational Experiential Inventory and The National Adult Reading Test) and one short task (Cambridge Gambling Task) will be added.

Ethical approval for the original study was granted on 6 April 2016.

Approval is given on the understanding that the UEL Code of Good Practice in Research is adhered to.

With the Committee's best wishes for the success of this project.

Please ensure you retain this letter, as in the future you may be asked to provide evidence of ethical approval for the changes made to your study.

Yours sincerely,

Fernanda Silva
Administrative Officer for Research Governance
University Research Ethics Committee (UREC)
Email: researchethics@uel.ac.uk

22nd February 2018

Dear Daniel,

Project Title:	**The effect of anodal stimulation of the right- and left-DLPFC on cognitive reflection**
Principal Investigator:	**Dr Volker Thoma**
Researcher:	**Daniel Edgcumbe**
Reference Number:	**UREC 1718 11**

I am writing to confirm the outcome of your application to the University Research Ethics Committee (UREC), which was considered by UREC on **Wednesday 15 November 2017.**

The decision made by members of the Committee is **Approved**. The Committee's response is based on the protocol described in the application form and supporting documentation. Your study has received ethical approval from the date of this letter.

Should you wish to make any changes in connection with your research project, this must be reported immediately to UREC. A Notification of Amendment form should be submitted for approval, accompanied by any additional or amended documents: http://www.uel.ac.uk/wwwmedia/schools/graduate/documents/Notification-of-Amendment-to-Approved-Ethics-App-150115.doc

Any adverse events that occur in connection with this research project must be reported immediately to UREC.

Approved Research Site

I am pleased to confirm that the approval of the proposed research applies to the following research site.

Research Site	**Principal Investigator / Local Collaborator**
Stratford campus, University of East London	Dr Volker Thoma

Approved Documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
UREC application form	2.0	5 December 2017
Rational Experiential Inventory (REI)	1.0	27 September 2017
Actively Open Minded Thinking scale (Stanovich & West, 2007)	1.0	27 September 2017
Participant Information sheet	2.0	5 December 2017
Consent form	.0	28 November 2017
Demographic Sheet	2.0	5 December 2017
Debrief after tDCS (tCS) session	1.0	27 September 2017
Research advert	1.0	27 September 2017
Standard procedure for Transcranial current stimulation (tCS) Recording and participant safety	1.0	27 September 2017

Approval is given on the understanding that the UEL Code of Practice in Research is adhered to.

The University will periodically audit a random sample of applications for ethical approval, to ensure that the research study is conducted in compliance with the consent given by the ethics Committee and to the highest standards of rigour and integrity.

Please note, it is your responsibility to retain this letter for your records.

With the Committee's best wishes for the success of this project.

Yours sincerely,

Fernanda Silva
Administrative Officer for Research Governance
University Research Ethics Committee (UREC)
Email: researchethics@uel.ac.uk