

**Cathodal Transcranial Direct Current Stimulation on Prefrontal Cortex: Examining  
Effects on Causal Learning in Adults**

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### **Abstract**

Over the past few decades, children have proven remarkable at acquiring abstract knowledge from very little evidence. In comparison with adults, children can be more open-minded, or better, at learning and endorsing unlikely solutions when supported by empirical evidence. Lucas et al. (2014) demonstrated that children are better at learning from causal data, while biases of adults weaken their ability to learn as effectively. Over the course of brain development, white matter increases and changes occur in synaptic connectivity within the cerebral cortex, helping to shape the way higher-level functions, like learning, are regulated. Specifically, the frontal lobes of the brain are highly connected to other cortical and subcortical regions and play a key role in higher-level cognitive processes and executive functions such as learning and reasoning. However, in children, the prefrontal regions have not yet fully developed to anatomical maturity and lag behind other cortical regions developmentally. This relative prefrontal immaturity of the developing brain corresponds with diminished cognitive control, or top-down inhibition, as well as a capacity for rapid, efficient learning. Adults who have experienced disruptions to prefrontal areas (via lesion or neural stimulation) demonstrate an artificial hypofrontality, leading to an increase in what could be considered creative capacity: quicker to solve unusual math problems, newfound artistic ability, or diminished functional fixedness. Chrysikou et al. (2013) demonstrated that using cathodal transcranial direct current stimulation (tDCS; a noninvasive neurostimulation method) over prefrontal regions of adults (specifically the left ventrolateral prefrontal cortex, or VLPFC) led to reduced top-down inhibition, and therefore faster reaction times when generating uncommon uses for objects. In this experiment, we examined whether applying the same cathodal tDCS to VLPFC of adults would result in diminished learning bias, hence, more open-mindedness when endorsing causal

structures. The uncommon uses task of Chrysikou et al. 2013 provided a positive control and a forward digit span task was used as a negative control. While data continues to be collected, the results are trending toward a subtle decrease of top-down constraints on cognition, allowing adults to endorse a more unusual hypothesis, as supported by the data.

*Keywords:* Causal learning, Overhypotheses, Ventrolateral prefrontal cortex, Cognitive control, Transcranial direct current stimulation

## **Introduction**

### *Causal Reasoning in Children and Adults*

Until relatively recently, child cognition was generally believed to be illogical, irrational, and engaged primarily in the here and now (Piaget 1929). Yet over the past thirty years, developmental psychologists have argued that the highly abstract representations that adults hold about the world are formed in early childhood. Research has demonstrated that given a limited amount of information, children are able to infer higher order properties (Schulz, Noah, Tenenbaum, & Jenkins 2008), form hypotheses and theories about the world around them (Gopnik 2012), and acquire knowledge of causal relations (Gopnik et al., 2004; Gweon & Schulz, 2011; Sobel & Kirkham, 2007; Kushnir & Gopnik, 2007; Schulz, Bonawitz, & Griffiths, 2007; Gopnik & Wellman, 2012).

One approach to explaining how we come to learn and understand the causal structure of the world around us is captured by the idea of “overhypotheses,” or abstract biases. These “overhypotheses” are essentially hypotheses about the hypotheses themselves, and help guide learners toward those that are more probable when inferring causal relations (Goodman, 1955;

Kemp, Perfors, & Tenenbaum, 2007). Goodman (1955) was the first to propose this idea, describing an “overhypothesis” as a higher-level prediction about a particular hypothesis (1955). In his example, a participant is given two bags of marbles, and discovers that one of the bags contains all black marbles and the other all white marbles. Then, given a third bag and drawing a blue marble, the participant would conclude that all marbles in the third bag are blue. Here, the particular hypothesis is that all the marbles in the bag are blue, but the *overhypothesis* is the (learned) higher-order principle that all marbles in each bag are the same color.

Hypotheses therefore describe the observed data, while overhypotheses constrain the space of hypotheses that are likely to be true. These biases are important for induction and inferring properties about novel entities (Kemp, Perfors, & Tenenbaum, 2007) because they provide generalizable knowledge that can inform new experiences beyond what is directly experienced.

Overhypotheses have served as a lens to explore models of probabilistic learning and have provided a perspective in addressing the question of how we come to learn so much so quickly. Dewar & Xu (2010) found in a looking time experiment that infants as young as nine months old are sensitive to overhypotheses. The infants were shown four identical boxes, from which were drawn blocks (blocks from a given box were all the same shape, but differing in color). From the fourth “test” box, objects were drawn that either matched each other in shape (expected outcome) or differed from each other in shape (unexpected outcome). Infants looked significantly longer at those objects in the unexpected outcome condition, suggesting that they had learned the overhypothesis that all blocks from a box are the same in shape. This evidence demonstrates that biases are not only learned, but also learned quite early in development. Smith, Jones, Landau, Gershkoff-Stowe and Samuelson (2002) demonstrated that 17-month-olds develop a shape bias to constrain categorization after relatively few training sessions.

Later, Kemp, Perfors, & Tenenbaum (2007) expanded on the nature of this learned shape bias by incorporating a hierarchical Bayesian model as a means of explaining *how* it is that these overhypotheses might be formed.

Recently, empirical research has begun to provide evidence for children's ability to learn these higher-order, abstract relationships, specifically in the domain of causal reasoning. Schulz, Goodman, Tenenbaum, & Jenkins (2008) found that four-year-olds given sparse data about causal relations of blocks used these relations to make judgments about the causal structure of novel blocks. Furthermore, they inferred an unobserved cause when they saw evidence that contradicted the causal law (Shultz et al., 2008).

While children are sensitive to overhypotheses from a young age (e.g. Shultz et al., 2008 and Dewar & Xu, 2010), how do these overhypotheses change into adulthood? Lucas, Bridgers, Griffiths, and Gopnik (2014) examine the extent to which children and adults differ in their generalization of abstract causal relations. Using the "blicket detector" paradigm (Gopnik & Sobel, 2000), in which certain objects activate the "blicket detector" machine, two causal structures were compared: the disjunctive (causal objects are disjunctive in the sense that they alone can activate the machine) and the conjunctive (requiring two causal objects in conjunction to activate the machine). While the conjunctive form does occasionally appear in everyday experience (e.g., a microwave must both be plugged in *and* the button must be pressed for it to work (Lucas et al., 2014), adults have greater experience learning the more common disjunctive causal structures with single element causation (Cheng, 1997; Griffiths & Tenenbaum, 2005; Lu, Yuille, Liljeholm, Cheng, & Holyoak, 2008). For example, the fire alarm going off could be either because someone pulled it for a fire drill, *or* because there is a real fire. It is less common for causation to take the form of multiple causes working in conjunction (e.g., both a fire drill

*and* the smoke of a fire). Because children have relatively low prior knowledge, they may be less likely to demonstrate a bias for the more common disjunctive abstract form.

The experiment presented children or adults with a machine called a “blicket detector” that plays music depending on which wooden blocks are placed on top (A, B, C). Participants were told that it was important to determine which of the blocks were “blickets” and that “blicketness” makes the machine turn on. Participants in the disjunctive condition were then shown evidence that only one block (*A or C*) was sufficient to make the machine go, and any time at least one of them was placed on the machine, it would turn on and play music. Participants in the conjunctive condition saw evidence that two blocks (*A and C*) were necessary to make the machine go, but no block successfully activated the machine alone.

After two training sets (demonstrating either the conjunctive or the disjunctive relation depending upon the condition), participants in both conditions were shown a test set of ambiguous evidence with new blocks (D, E, F), and asked to make judgments about whether each block was a “blicket.” Both children and adults performed similarly at inferring the causal structure of novel objects after seeing the disjunctive evidence. However, after observing conjunctive evidence, the children were able to correctly generalize that causal structure to novel objects while adults did not. Instead, the adults demonstrated a bias toward the disjunctive structure regardless of the training evidence they were shown (Lucas et al., 2014). These results are interpreted to suggest that children’s lower levels of prior knowledge result in fewer constraints on their hypothesis space, and more open-minded, or flexible, approaches when considering possible causal relations. Adults on the other hand, have greater levels of prior knowledge when making inferences, resulting in the incorporation of a learned bias when approaching new learning situations.

*Prefrontal Cortex Development & Cognition*

In examining the possible origins for the development of this learning bias, we turn to an area of the cortex that is primarily implicated in cognition, semantic retrieval, and abstract reasoning: the prefrontal lobes. As the developing brain edits connectivity and relative amounts of gray and white matter, the frontal lobes remain one of the final areas to become fully mature, allowing for significant structural and connectivity differences between the frontal regions of a child and that of an adult.

In the first half of the 1900s, the frontal lobes of the brain were thought to be relatively unimportant in neurological functioning. The frontal cortex is now considered home to most high-level “executive” functions of human cognition, including abstract representation, top-down modulation, planning, reasoning, and goal oriented behavior (e.g., Mars & Grol 2007; Botvinovk, Nystrom, & Fissell 1999; Ridderinkhof, Ullsperger & Crone 2004; Shallice, Burgess 1991; Goel 2004; Koechlin 2003; Stuss and Knight, 2013). Yet the frontal lobes undergo an extended period of development, and are among the last areas of the brain to fully myelinate and stabilize synaptic connections (e.g., Pfefferbaum et al., 1994; Giedd, Blumenthal & Jeffries 1999; Sowell, Thompson, Tessner, & Toga, 2001). Synaptogenesis occurs throughout fetal development and early childhood, creating far more connections than eventually is necessary. This period of overgrowth is followed by synaptic pruning, or the elimination of underutilized connections (Chechik, Meilijson, & Ruppín, 1999; Selemon, 2013).

In most species, including the Rhesus Macaque old-world monkey, synaptogenesis and pruning occur simultaneously throughout the cortex (Rakic et al. 1986). Humans however experience a slower peak of synaptogenesis in higher cortical areas (e.g. frontal lobes), lagging behind areas of primary modalities (Huttenlocher & Dabholdar, 1997). This anatomical

immaturity translates to fewer constraints in regulating executive function, less top-down cognitive control, and more upregulation of subcortical structures (Jäncke 2009). Children whose brains have yet to fully develop therefore exhibit “impaired behavioral and cognitive control – akin to patients with neurological PFC damage” (Thompson-Schill, Ramscar, & Chrysikou 2009). The correlation of prefrontal cortical damage and behaviorally similar outcomes as developing brains, suggests those areas as critical in shaping cognition over time.

This relative hypofrontality (i.e., diminished activity of the frontal lobes) seen in the developing brain can paradoxically be favorable for more optimal learning in certain situations (Thompson-Schill, Ramscar, & Chrysikou 2009). Children younger than four years old generally overmatch probability, therefore maximizing chances of accuracy, yet with development, they move closer to probability matching (Derks & Paclisanu, 1967). Other evidence suggests that children, unlike adults, are immune to functional fixedness (German & Defeyter, 2000). Given a number of objects and a goal to execute, children are not constrained by the typical use for the objects, but instead are able to utilize objects in light of the present goal even if that use is unconventional and distinct from the common use.

This research contributes to ideas of the Lucas et al. (2014) study, in offering further evidence that children are sometimes better at aspects of learning. This phenomenon can be tied to the delayed maturation of areas of the brain critical to cognition and reasoning such as prefrontal cortex, and suggests that this relative underdevelopment in children allows for such efficient learning behavior

### *Cognitive Control & the Role of the Prefrontal Cortex*

The frontal lobes, although later to mature are important in many executive functions, and also play an important role in cognitive control. Cognitive control promotes the top-down



inhibition of inappropriate responses for the task at hand and allows for the faster, more efficient performance of many common activities – essentially helping to coordinate information from other regions of the brain and selecting relevant actions. In the 1970s, Aleksandr Luria proposed the role of the prefrontal cortex as a “superstructure [...] that perform[s] a far more universal function of general regulation of behavior than that performed by the posterior associative centre” (Luria 1973). Miller & Cohen discuss this cognitive control function of the frontal lobes as coordinating lower level processes toward an internal goal (2001). The frontal regions are extensively connected and communicate broadly with brain regions – ventrolateral areas are particularly well connected to both cortical and subcortical regions (Miller & Cohen, 2001). This connectivity allows for the prefrontal areas to form a pattern of activity suspected as a retrieval mechanism for abstract concepts (Napponey & Price, 2004). For example, Napponey & Price (2004) found that the left frontotemporal system was particularly involved when making semantic judgments regarding whether words were synonymous. Thompson-Schill et al. (2005) found further support that prefrontal cortex supports semantic retrieval, or “semantic working memory.” Ongoing research continues to provide evidence that frontal systems are critical for top-down coordination and semantic retrieval (Poldrack et al., 1999; Wagner et al. 2001; Thompson-Schill et al., 2002). In this study, we hope to connect research examining coordinated retrieval of semantic information to the development of learned biases in adults. Presumably, this coordinated retrieval is developed over time simultaneously to learning biases, and may offer an anatomical correlate to how these biases are extracted and incorporated into cognition.

Behavioral, imaging, and neurostimulation studies have bolstered evidence that the prefrontal cortex supports this function, and when disturbed, can result in an alleviation of top-

down cognitive control. Much of the neurological testing used to examine executive function indicates that the frontal lobes act as a cognitive control mechanism. The Stroop task, for example, asks participants to say the color of ink used for words while the words themselves are the names of colors. Inhibiting the initial response (the stronger competitor) to read the word, and instead quickly being able to say the color of the ink used in the word on many trials is considered a successful performance. Patients with frontal lobe lesions struggle to perform this task, suggesting that the prefrontal cortical areas are crucial in inhibiting certain responses and selecting the appropriate one.

Furthermore, patients who have pathological damage to the frontal lobes show benefits in creativity, or at the least, an alleviation of top-down inhibition of more usual responses or behavior. For example, Seeley et al. (2008) studied a patient with frontotemporal dementia (a neurodegenerative disease selective for the temporal and frontal lobes) who, experienced newfound artistic expression and ability as the disease progressed. Relatedly, in a study of frontal lesion patients, Reverberi (2005) tested individuals with damage to the prefrontal cortex using the matchstick task – a cognitive task that requires participants to “think outside the box” in order to find the correct solution. Participants were given a number of mathematical equations written in Roman numerals and asked to make the mathematical statement true by moving just one of the matchsticks used to write the equation. Each equation had a different type of manipulation required to make the statement true. The more conventionally solved problem involved manipulating a ‘I’ Roman numeral, for example moving a matchstick to make “VI = VII + I” into the true statement “VII = VI + I.” The problems requiring a more “creative” solution necessitated moving a matchstick to make a “+” sign instead of an “=” sign, for example, to make “IV = IV + IV” read “IV = IV = IV.” Reverberi found that frontal lesion

patients (with a damaged portion of their prefrontal cortex due to stroke or other clinical pathology) were nearly two times better at solving this problem of insight (Reverberi 2005).

Evidence from other methodologies contributes to our understanding of the role of the prefrontal cortex in cognitive control. For example, a functional MRI study examined jazz musicians in the scanner as they either played an over-rehearsed musical sequence or an improvisational sequence. During the improvisational sequence, areas such as the dorsolateral and orbital lateral regions showed large patterns of deactivation (Limb & Braun, 2008), suggesting that the “shutting down” of frontal areas begets the ability for more creative musicality. Furthermore, an electroencephalography (EEG) study comparing convergent vs. divergent thinking found diminished activity in frontal cortical areas of those participants who were more successful at solving a problem that required divergent thinking (Mölle et al., 1999).

Recently, neurostimulation methods have been used to further examine the role of prefrontal areas in regulating cognitive functioning and control. Transcranial direct current stimulation (tDCS) is a noninvasive neurostimulation technique, commonly used for clinical and experimental brain modulation (Stagg et al., 2013; Clark et al., 2012; Cerruti & Schlaug 2009; Chrysikou, Weber, & Thompson-Schill 2013). TDCS consists of two electrodes: an anode and a cathode, both of which modulate cortical excitability via cell membrane resting state voltage. The anode (A-tDCS) increases cortical excitability and cell signaling by depolarizing the soma (cell body) of the neuron, while cathodal (C-tDCS) decreases excitability by hyperpolarizing the soma (Medeiros et al, 2012; Nitsche et al., 2008; Stagg & Nitsche, 2001). One of these two functions is usually of primary interest, but both electrodes must make contact with the scalp such that the current can flow between them.

Previous research has demonstrated that application of the anodal tDCS electrode over frontal areas has resulted in improved inhibitory control and working memory (Jacobson & Lavidor, 2011; Javadi & Walsh, 2012; Boggio et al., 2006). Chi and Snyder (2011) used the same insight problem that Reverberi (2005) used when testing lesion patients, but, instead of lesions, Chi's participants received cathodal tDCS to the anterior temporal lobe. Results show that depressed brain activity led to a dramatic increase in the number of insightful solution (Chi & Snyder 2011), leading to their claim that "our experiences can blind us" (Chi & Snyder 2011). This statement also speaks to the results of the Lucas et al. (2014) experiment, describing the tendency of to be worse at generalizing from evidence due to a previously held bias.

Recently, Chrysikou et al. (2013) also utilized cathodal tDCS over left frontal cortex (VLPFC), examining its effects on a creativity task: the generation of unusual uses for objects. Participants were divided into conditions that counterbalanced sham vs. stimulation, left hemispheric stimulation vs. right hemispheric stimulation, and generation of common vs. uncommon uses. To identify the ideal electrode montage Chrysikou et al. (2013) used fMRI imaging and finite element methods (FEM) to identify the left VLPFC as the location for stimulation, as well as how best to place electrodes such that current peaked under the area of interest. Participants were presented with a series of gray-scale images of everyday objects via E-Prime software, and asked to produce either a common or an uncommon use for the object. Results showed that participants receiving cathodal tDCS stimulation over the left VLPFC were significantly faster at generating uncommon uses for objects.

### *Overview of the Current Study*

The current study examines the effects of applying the same tDCS electrode montage used in Chrysikou et al. (2013) to the left VLPFC of adults and examining how this affects

causal learning. As reviewed above, reasoning about novel situations requires consideration of multiple competing hypotheses and involves top-down control of which to select. In making judgments about causal structures, we suggest that cognitive control plays an important role in orchestrating the extraction of semantic knowledge and incorporating these priors into online reasoning. In other words, this area of the brain is expected to play a key role in selecting information from more distant or subcortical regions of the brain, and therefore contributes to the dampening of more unlikely hypotheses and the strengthening of more likely ones.

Lucas et al. (2014) demonstrated that when learning empirically correct but less common causal structures, adults displayed a learning bias toward the common disjunctive structure. Children, on the other hand, learned more effectively from the data presented and more readily endorsed the conjunctive structure of abstract causality as a result. Children were therefore more flexible in situations of reasoning and learning about more unusual causal structures of the world, in particular, when considering causal relations. In the current experiment, we will conduct the causal learning task as presented in Lucas et al. (2014) as well as the uncommon uses task (Chrysikou et al. 2013) and a forward digit span task as controls. We hypothesize that adults receiving cathodal tDCS to the left VLPFC will demonstrate an increase in their willingness to endorse the more unusual conjunctive causal structure, and differ in their judgments of the novel block D compared to those participants receiving sham.

## **Methods**

The current experiment is composed of three tasks: the causal learning task from Lucas et al. (2014), the uncommon uses task from Chrysikou et al. (2013), and a forward digit span task. The uncommon uses tasks provides us with a positive control experiment in which we

would expect to see replicated effects as those in Chrysikou et al. (2013). The forward digit span task on the other hand, provides a negative control, and thus, we expect to see no differences in performance across on conditions. All tasks were conducted following either cathodal tDCS to the left VLPFC or no stimulation (sham).

## Participants

Participants were 42 undergraduates ( $M = 21.79$  years; range = 19-39 years;  $SD = 3.33$ ) recruited from the University of California, Berkeley, participating in exchange for class credit. An additional three participants were excluded from the study due to equipment malfunction resulting in incorrect presentation of evidence in the causal learning task. Participants were randomly assigned to one of four conditions either receiving cathodal tDCS stimulation to the left VLPFC or sham stimulation (same placement), and either seeing disjunctive evidence in the causal learning task or conjunctive evidence: disjunctive with stimulation ( $n = 10$ ,  $M = 21.5$  years, range = 19-28 years;  $SD = 2.6771$ ), disjunctive with sham ( $n=10$ ,  $M = 24.0$  years, range = 20-39 years;  $SD = 5.5976$ ), conjunctive with stimulation ( $n=11$ ,  $M = 20.6$  years, range = 19-26 years,  $SD = 2.0136$ ), conjunctive with sham ( $n=11$ ,  $M = 21.2$  years, range = 20-23 years,  $SD = 0.8738$ ). Participants were blind to their assigned condition.

## Materials

In the uncommon uses task, thirty gray scale pictures of everyday objects (448 x 336 ppi) were presented via E-Prime software on a desktop computer (see Figure 1a-b). These images were originally created as part of the Uses Task in Chrysikou and Thompson-Schill (2011), and then later used in Chrysikou et al. (2013). However, of the sixty images used in the Chrysikou et al. (2013), only thirty were presented in this study in order to conduct all three tasks while keeping the duration of tDCS under twenty minutes. The images were displayed on

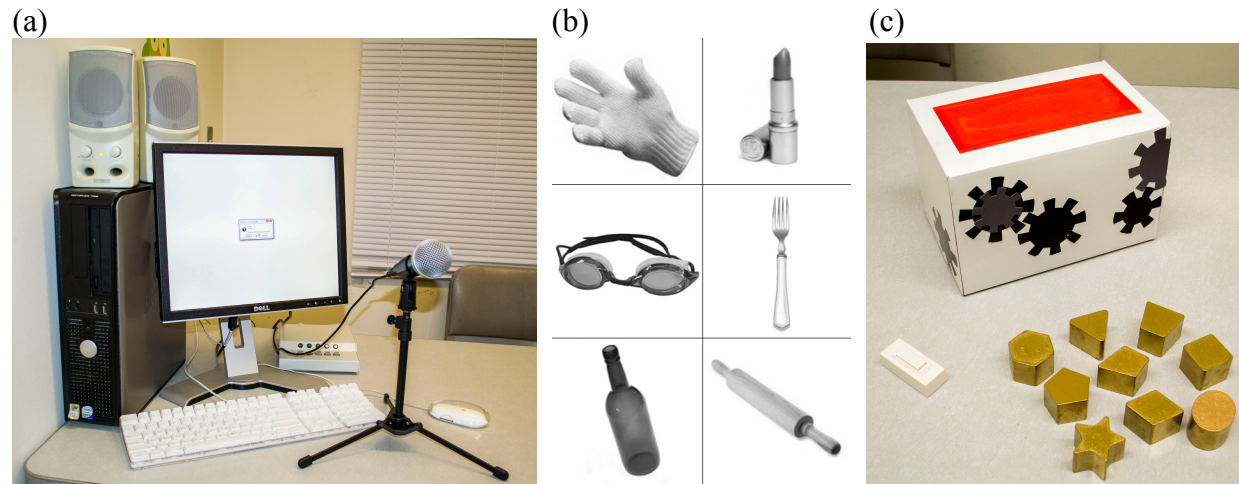
a gray background for 9000ms each, with an interstimulus interval of 3000ms. Order of images was randomized across participants. A microphone connected to a serial recording box recorded vocal reaction time. The experimental session was videotaped and used to code responses of participants.

For the causal learning task, a cardboard box (approximately 40x25x25cm) was used as the blicket machine and painted with gears to give an artistic impression of functionality. A wireless doorbell was placed inside the box, and the doorbell switch was kept below the table allowing for the experimenter to activate the doorbell with her foot. Thus, the activation via the hidden doorbell switch gave participants the impression that the block(s) being placed on the machine at the time caused the activation. Eleven wooden blocks, all unique shapes, were purchased and spray-painted gold. These blocks functioned as the items judged to be blickets or not. Blocks were randomly selected for order of presentation in each experimental session (three blocks for the first training trial, three blocks for the second training trial, and three blocks for the ambiguous test).

The tDCS device used was a Phoresor II Auto model by Iomed, Inc. and used in conjunction with a standard multimeter. An EEG 10-20 cap manufactured by Guger Technologies guided placement of electrodes at the desired positions.

## **Procedure**

Participants were randomly assigned to one of four conditions based on causal relation and stimulation parameters. We chose a between subject design due to the exclusive nature of both the causal learning task and the uncommon uses task such that one participant cannot participate in both conditions.



**Figure 1.** (a) Computer monitor and microphone set up for Uncommon Uses task. (b) Example images used in Uncommon Uses task. (c) Blicket detector machine, blocks, and wireless doorbell used for the Causal Learning task.

Participants were seated in front of a table and completed informed consent documents, a tDCS screening form, and a media consent form. Participants were then read instructions to all three tasks (order of causal learning task and uncommon uses task was counterbalanced, and forward digit span was always last).

Following brief instructions of all three tasks, the electrode montage from Chrysikou et al. (2013) and Chrysikou & Thompson-Schill (2011) was set up. An EEG 10-20 cap indicated the F7 region of interest corresponding to the left VLPFC. After the placement of an elastic strap, the cathodal electrode was placed on the F7 mark, and the anodal electrode was placed on the contralateral (right) mastoid bone, just behind the ear. The tDCS parameters were set for a current of 1.5mA with a dosage of 30mA\*minute, meaning that a 1.5mA current would be running for twenty minutes. These parameters were duplicated from the Chrysikou et al. (2013) paper and abide within previously established safety limits (e.g., Bikson, Datta, & Elwassif, 2009; Nitsche et al., 2003; Tadini et al., 2011). Under simulation parameters, the current ramped up for ninety seconds in order to have significant efficacy of the current flow before the experimenter began the tasks. Under sham conditions, the current was ramped up momentarily



to give the illusion of stimulation, but was immediately ramped down to 0mA (completely off) for the remainder of the experiment.

Following the ramp-up of current, participants either began the uncommon uses task or the causal learning task depending on their condition. The order of the causal learning task and the uncommon uses task was counterbalanced across participants. The forward digit span task was placed at the end because no order effect was found when counterbalanced in Chrysikou et al. 2013.

For the uncommon uses task, participants were instructed to come up with a novel use for the object. They were told there was no correct or incorrect response, and that they should respond with whatever answers came to mind. They were asked to generate responses as fast as possible and remain silent if they did not have an answer to give. In the initial instruction block, participants were given a brief training session consisting of three items. The uncommon uses tasks consisted of thirty images, and lasted approximately six minutes.

In the causal learning task, participants were given an answer packet in which they recorded their responses. Participants were then shown a box filled with gold blocks of all different shapes. The experimenter informed them that in the game the goal was to try to figure out which of the things (golden blocks) were blickets, and that even though blicketness cannot be distinguished just by looking at the objects, blickets do have something called blicketness inside of them. Then participants were introduced to the blicket detector and told that what was special about the machine was that blicketness made the machine turn on and play music. Participants then observed two training sets of data. Each of the two times, three blocks (A, B, C) were drawn randomly from the box containing all the blickets and labeled by the experimenter with their corresponding shape. In the training conditions, blocks A, B, and C

were placed alone and in pairs on the machine, and sometimes the machine would activate, other times it would not depending on the causal structure of the participant's condition, see Figure 2. Following the activation pattern, the experimenter asked participants to write down the item name in their answer packet and indicate whether they thought each of the three items was a blicket (yes) or not a blicket (no).

After the two training sessions, a test session was administered consisting of three novel objects (D, E, F), which were similarly labeled according to their shape. Regardless of causal structure condition, participants were shown the same pattern of test evidence (Figure 2).

Participants were then asked to record the item name and indicate whether they thought each of the three items was a blicket (yes) or not a blicket (no). Once participants had turned the page, they were asked to indicate the probability that they thought each of the novel items was a blicket (0 = certainly not a blicket, 5 = equally likely, 10 = certainly a blicket). Finally, on the last page, participants were asked to indicate which of the items should be used to make the machine turn on. The question was intentionally ambiguous in order to support any combination of the three blocks. The entire causal learning task lasted approximately eight minutes.

After the uncommon uses task and the causal learning task, the forward digit span task was conducted with the experimenter standing behind the participant to prevent the use of visual input. The experimenter read sixteen strands of increasingly long strings of numbers were read and the participant repeated them back in the same order. When a participant made an error on two consecutive strings of the same length, the task was stopped. The forward digit task lasted approximately four minutes. Participants received one point for each correctly recited number span.

## Coding and Reliability

For the uncommon uses task, reaction times were extracted from the E-Prime data file and the experimenter later transcribed responses from the video recording. Individual responses were omitted if there was no answer provided, the microphone failed to register a reaction time, or if the response violated the instructions: (a) gave the typical common use for the object (b) was substantially unclear, or (c) was obviously inappropriate for the object (e.g., pencil = to wear as glasses). Two blind coders omitted answers with a similarity of 93.75%; a blind third party resolved discrepancies. If the number of total response omissions exceeded fifteen for any participant (half of the thirty total responses per participant), then the participant was dropped due to concern that the remaining reaction times were not representative.

For the causal learning data, following the entire session, the experimenter entered the participant's responses from the answer packet into the computer. Similarly, the forward digit span score was entered into the computer at the end of the session. At the end of data collection, the experimenter re-entered the data with no discrepancies.



**Figure 2.** Graphic from Lucas et al. (2014) illustrating the pattern of blicket detector activation in the conjunctive, disjunctive, and test patterns of evidence.

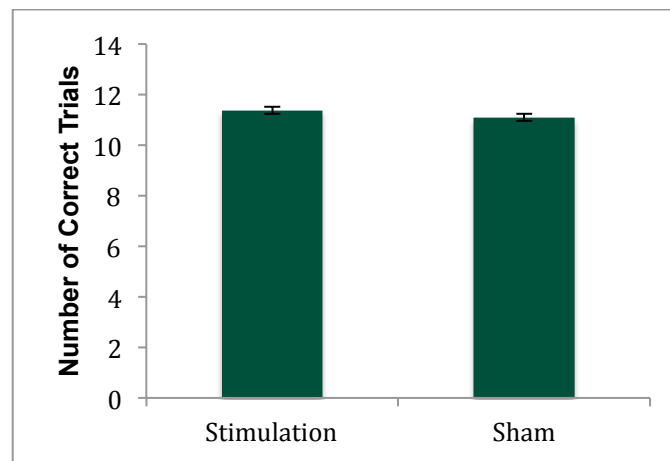
## Results

All participants completed the study with no report of adverse effects or other discomfort. Results were analyzed for the forward digit span task, the causal learning task, and the uncommon uses task to assess the effects of stimulation. No differences were found between

the stimulation vs. sham participants on the forward digit span task or the uncommon uses task. On the causal learning task, no differences were found in the disjunctive condition. In the conjunctive condition, certain differences were significant but for the primary question (are those receiving stimulation more likely to endorse D as a blicket than those receiving sham?), results are trending but not significant toward a subtle difference in labeling block D as a blicket.

### *Forward Digit Span*

No significant differences were found in performance on the forward digit span task between participants receiving stimulation ( $M = 11.38$ ,  $SD = 2.38$ ) and those receiving sham ( $M = 11.09$ ,  $SD = 2.36$ ;  $p = 0.6986$ , two-tailed t-test). See Figure 3.



**Figure 3.** Performance on forward digit span task: stimulation vs. sham conditions. Error bars show standard error.

### *Causal Learning: Disjunctive Condition (Binary)*

Participants in the stimulation and sham conditions provided the same pattern of responses when shown disjunctive evidence (see Figure 4). Those receiving stimulation labeled block F ( $M = 0.9$  of 1,  $SD = 0.32$ ) a blicket more often than D ( $M = 0$  of 1,  $SD = 0$ ;  $p < .001$ , one-tailed Fisher's exact) or E ( $M = 0$  of 1,  $SD = 0$ ;  $p < .001$ , one-tailed Fisher's exact).

Participants receiving sham stimulation also labeled block F ( $M = 1$  of 1,  $SD = 0$ ) a blicket more often than D ( $M = 0$  of 1,  $SD = 0$ ;  $p < .001$ , one-tailed Fisher's exact) or E ( $M = 0$  of 1,  $SD = 0$ ;  $p < .001$ , one-tailed Fisher's exact).

There was no difference between stimulation and sham condition in judgments of blocks D, E, or F: D and E were not labeled blickets, while F was labeled a blicket. Neither participants receiving stimulation ( $M = 0$  of 1,  $SD = 0$ ) nor sham ( $M = 0$  of 1,  $SD = 0$ ) labeled block D a blicket ( $p < .001$ ,  $p < .001$ , respectively, one-tailed exact binomial). Similarly, neither participants receiving stimulation ( $M = 0$  of 1,  $SD = 0$ ) nor sham ( $M = 0$  of 1,  $SD = 0$ ) labeled block E a blicket ( $p < .001$ ,  $p < .001$ , respectively, one-tailed exact binomial). Both those receiving stimulation ( $M = 0.9$  of 1,  $SD = 0.32$ ) and those receiving sham ( $M = 1$  of 1,  $SD = 0$ ) labeled block F as a blicket ( $p = .011$ ,  $p < .001$ , respectively, one-tailed exact binomial). There were no significant differences between stimulation and sham participants in judgments of blocks D ( $p = 1$ , one-tailed Fisher's exact), E ( $p = 1$ , one-tailed Fisher's exact), or F ( $p = .50$ , one-tailed Fisher's exact).

*Causal Learning: Conjunctive Condition (Binary)*

Participants in the stimulation and sham conditions demonstrated similar patterns of responses when shown conjunctive evidence, although there is a trend toward a difference in response to block D. Those receiving sham labeled block F ( $M = 0.8182$  of 1,  $SD = 0.4045$ ) a blicket more often than D ( $M = .1818$  of 1,  $SD = .4045$ ;  $p = 0.004$ , one-tailed Fisher's exact) or E ( $M = .1818$  of 1,  $SD = .4045$ ;  $p = 0.004$ , one-tailed Fisher's exact).

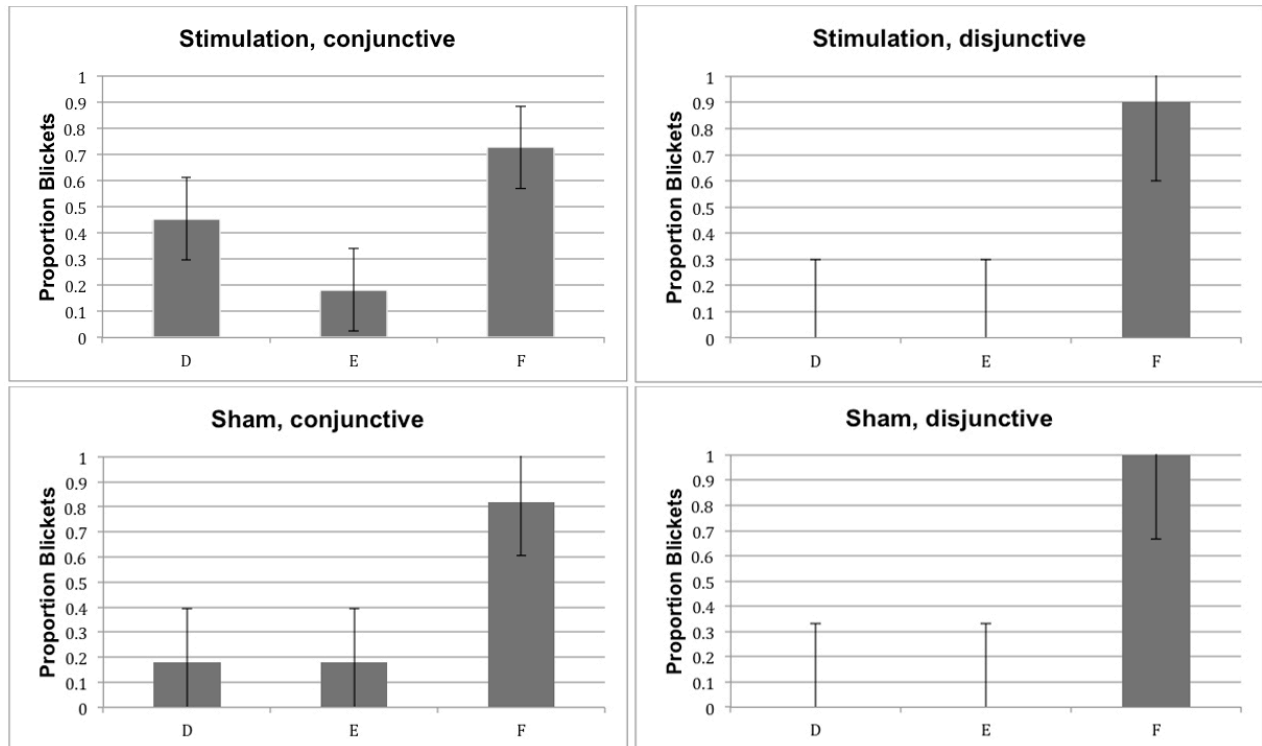
Participants receiving stimulation also labeled block F ( $M = .7273$  of 1,  $SD = .4671$ ) a blicket more often than E ( $M = .1818$  of 1,  $SD = .4045$ ;  $p = 0.015$ , one-tailed Fisher's exact). However, unlike participants in the sham condition, participants receiving stimulation did *not*

judge F to be a blicket significantly more often than D ( $M = 0.4546$  of 1,  $SD = 0.5222$ ;  $p = 0.1934$ , one-tailed Fisher's exact). *These results suggest that the application of tDCS led to greater sensitivity to the conjunctive training evidence.*

Participants receiving stimulation and sham did not significantly differ in their judgments of blocks D ( $p = 0.1807$ , one-tailed Fisher's exact), E ( $p = 0.7068$ , one-tailed Fisher's exact), or F ( $p = 0.500$ , one-tailed Fisher's exact). While these results do not show a significant difference in judgments of block D, the data is trending.

Finally, those receiving stimulation in the *conjunctive* condition ( $M = 0.4546$  of 1,  $SD = 0.5222$ ) significantly differed in their judgment of D compared to those receiving stimulation in the *disjunctive* condition ( $M = 0$  of 1,  $SD = 0$ ,  $p = 0.023$ , one-tailed Fisher's exact). Participants receiving sham in the *conjunctive* condition ( $M = 0.1818$  of 1,  $SD = 0.4045$ ) did not significantly differ in their judgment of D compared to those receiving sham in the *disjunctive* condition ( $M = 0$  of 1,  $SD = 0$ ,  $p = 0.262$ , one-tailed Fisher's exact). *Given conjunctive evidence, unlike participants receiving sham, those receiving stimulation were more likely to correctly endorse D (as well as F) when given conjunctive training evidence.*

Participants in the stimulation and sham conditions provided the same pattern of responses when shown disjunctive evidence (see Figure 5). Those receiving stimulation labeled block F ( $M = 8.8$  of 10,  $SD = 2.7809$ ) a blicket more often than D ( $M = 0.3$  of 10,  $SD = 0.94868$ ;  $p < .001$ , one-tailed t-test) or E ( $M = 1.5$  of 10,  $SD = 2.7588$ ;  $p < .001$ , one-tailed t-test). Participants receiving sham stimulation also labeled block F ( $M = 9.9$  of 10,  $SD = 0.3162$ ) a blicket more often than D ( $M = 0.3$  of 10,  $SD = 0.9487$ ;  $p < .001$ , one-tailed T-test) or E ( $M = 1$  of 10,  $SD = 1.8856$ ;  $p < .001$ , one-tailed t-test), confirming results of the binary blicketness ratings as well as results from previous literature.



**Figure 4.** Proportions of blocks in the test trial judged as blickets (1 = blicket, 0 = not a blicket). D is the conjunctively active object, E is uncertain, and F is the unambiguous (active) block.

#### *Causal learning: Disjunctive (Probabilities)*

In the disjunctive condition, there was no difference between stimulation and sham conditions in judgments of blocks D, E, or F: D and E were not labeled blickets, while F was labeled a blicket. Neither participants receiving stimulation ( $M = 0.3$  of 10,  $SD = 0.9487$ ) nor sham ( $M = 0.3$  of 10,  $SD = 0.9487$ ) labeled block D a blicket ( $p < .001$ ,  $p < .001$ , respectively, one-tailed single sample t-test). Similarly, neither participants receiving stimulation ( $M = 1.5$  of 10,  $SD = 2.7588$ ) nor sham ( $M = 1$  of 10,  $SD = 1.8856$ ) labeled block E a blicket ( $p = .002$ ,  $p < .001$ , respectively, one-tailed single sample t-test). Both those receiving stimulation ( $M = 8.8$  of 10,  $SD = 2.7809$ ) and those receiving sham ( $M = 9.9$  of 10,  $SD = 0.3162$ ) labeled block F as a blicket ( $p < .001$ ,  $p < .001$ , respectively, one-tailed single sample t-test). There were no

significant differences between stimulation and sham participants in judgments of blocks D ( $p = 0.5$ , one-tailed t-test), E ( $p = 0.3220$ , one-tailed t-test), or F ( $p = 0.2309$ , one-tailed t-test).

*Causal Learning: Conjunctive Condition (Probabilities)*

Participants in the stimulation and sham conditions demonstrated similar patterns of responses when shown conjunctive evidence. There was a weaker, although analogous trend to that of the binary data with respect block D judgments. Those receiving sham gave a higher probability of blicketness to block F ( $M = 8.7273$  of 10,  $SD = 1.8488$ ) than D ( $M = 2.3636$  of 10,  $SD = 2.5009$ ;  $p = 0.001$ , one-tailed t-test) or E ( $M = 2.2727$  of 10,  $SD = 2.7961$ ;  $p < 0.001$ , one-tailed t-test).

Participants receiving stimulation also gave block F ( $M = 8.5455$  of 10,  $SD = 2.1149$ ) a higher probability of blicketness than D ( $M = 3.6363$  of 10,  $SD = 2.9064$ ;  $p = 0.004$ , one-tailed t-test), or E ( $M = 3.0909$  of 10,  $SD = 2.3002$ ;  $p < 0.001$ , one-tailed t-test). This significant difference in the judgments of D and F stands in contrast to the result of the binary judgments by those receiving stimulation in the conjunctive condition.

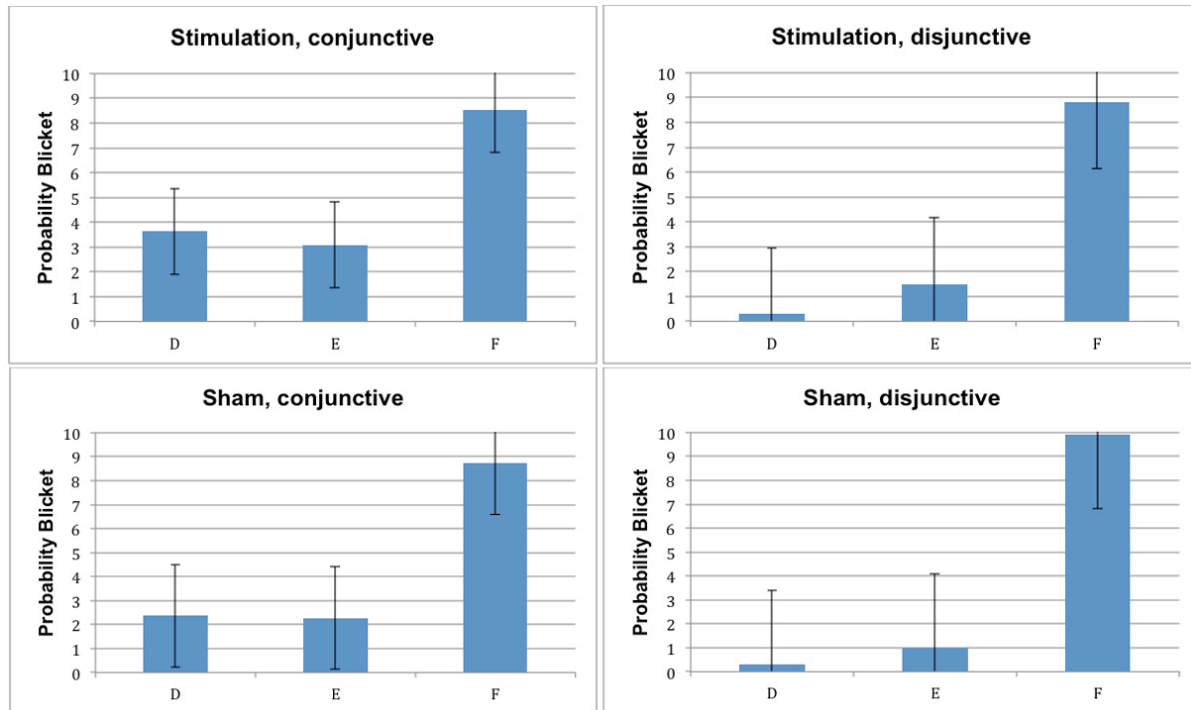
Participants receiving stimulation and sham did not significantly differ in their judgments of blocks D ( $p = 0.1718$ , one-tailed t-test), E ( $p = 0.2310$ , one-tailed t-test), or F ( $p = 0.4179$ , one-tailed t-test). However, while these results do not show a significant difference in judgments of block D, the data is trending similarly to the binary judgments.

Finally, those receiving stimulation in the *conjunctive* condition ( $M = 3.6363$  of 10,  $SD = 2.9064$ ) significantly differed in their judgment of D compared to those receiving stimulation in the *disjunctive* condition ( $M = 0.3$  of 10,  $SD = 0.94868$ ,  $p = 0.005$  one-tailed t-test).

However, participants receiving sham in the *conjunctive* condition ( $M = 2.3636$  of 10,  $SD = 2.5009$ ) *also* significantly differed in their judgment of D compared to those receiving sham in



the *disjunctive* condition ( $M = 0.3$  of 10,  $SD = 0.9487$ ,  $p = 0.012$ , one-tailed t-test). This result stands in contrast to that of the binary responses, and instead suggests that both participants receiving stimulation and those receiving sham are somewhat sensitive to the training conjunctive evidence.



**Figure 5.** Probability ratings of blicketness for blocks in the test trial (10=certainly blicket, 0=certainly not a blicket). D is the conjunctively active object, E is uncertain, and F is the unambiguous block.

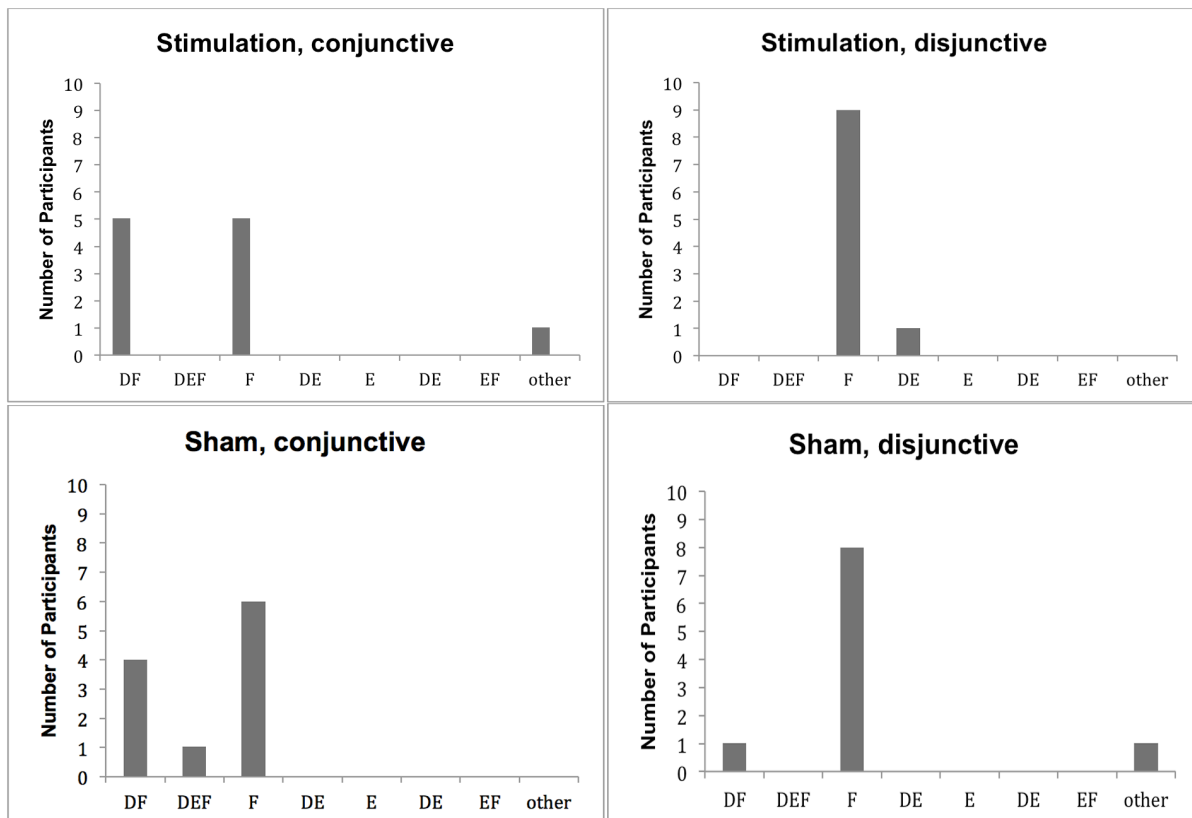
### *Causal Learning: Interventions*

As the final question of the causal learning task, participants were asked, “which of these blocks should we use to make the machine go?” referring to blocks D, E, and F (see Figure 6). Those receiving stimulation in the conjunctive condition did not make choices containing D significantly more than half the time ( $p = 0.500$ , one-tailed binomial test), nor did they make choices containing multiple objects significantly more than half the time ( $p = 0.500$ , one-tailed binomial test). Similarly, participants receiving sham in the conjunctive condition did not make

choices containing D significantly more than half the time ( $p = 0.6230$ , one-tailed binomial test) or make choices containing multiple objects significantly more than half the time ( $p = 0.6230$ , one-tailed binomial test).

However, participants receiving *stimulation* chose answers involving D in the conjunctive condition significantly more often than their counterparts in the disjunctive condition ( $p = 0.0426$ , one-tailed Fisher's exact), while those receiving sham did not show this distinction ( $p = 0.2214$ , one-tailed Fisher's exact).

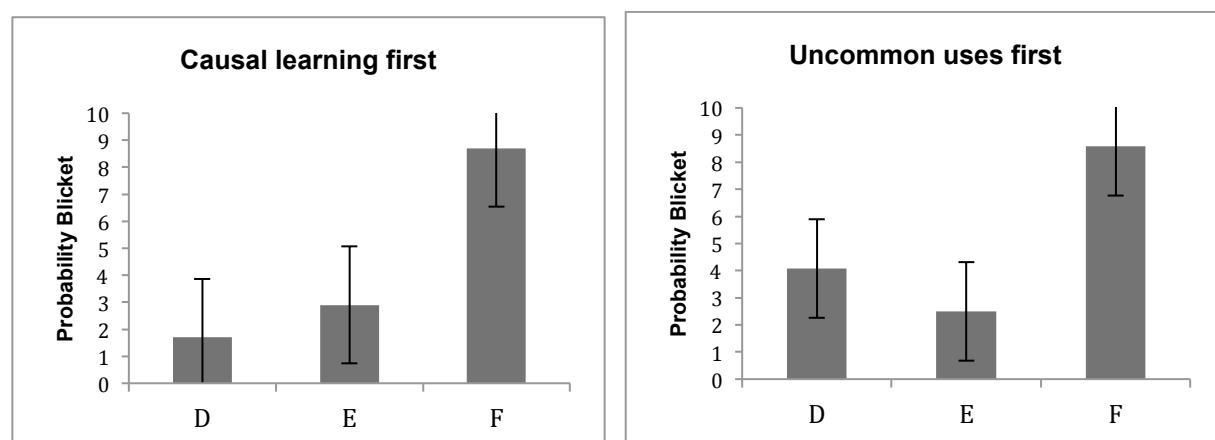
Across the disjunctive condition, those receiving stimulation chose F significantly more than any other option ( $p = 0.0107$ , one-tailed binomial), and similarly, those receiving sham came just shy of choosing F significantly more than any other option ( $p = 0.0547$ , one-tailed binomial).



**Figure 6.** Participants' choices for the intervention question across stimulation and causal structure condition.

### *Causal Learning: Order Effects*

Due to the nature of tDCS, in which effects can increase with time, we performed an analysis on the order in which the causal learning task and the uncommon uses task was performed for those participants in the conjunctive condition. While no significant differences were seen in the binary labeling of blocks D, E, or F, those who participated in the uncommon uses task first ( $M = 4.083$  of 10,  $SD = 3.3428$ ) gave block D a significantly higher *probability* rating than those who participated in the causal learning task first ( $M = 1.7$  of 10,  $SD = 2.2136$ ,  $p = 0.0340$ , one-tailed t-test), regardless of stimulation condition, see Figure 7. This suggests a small yet significant order effect.



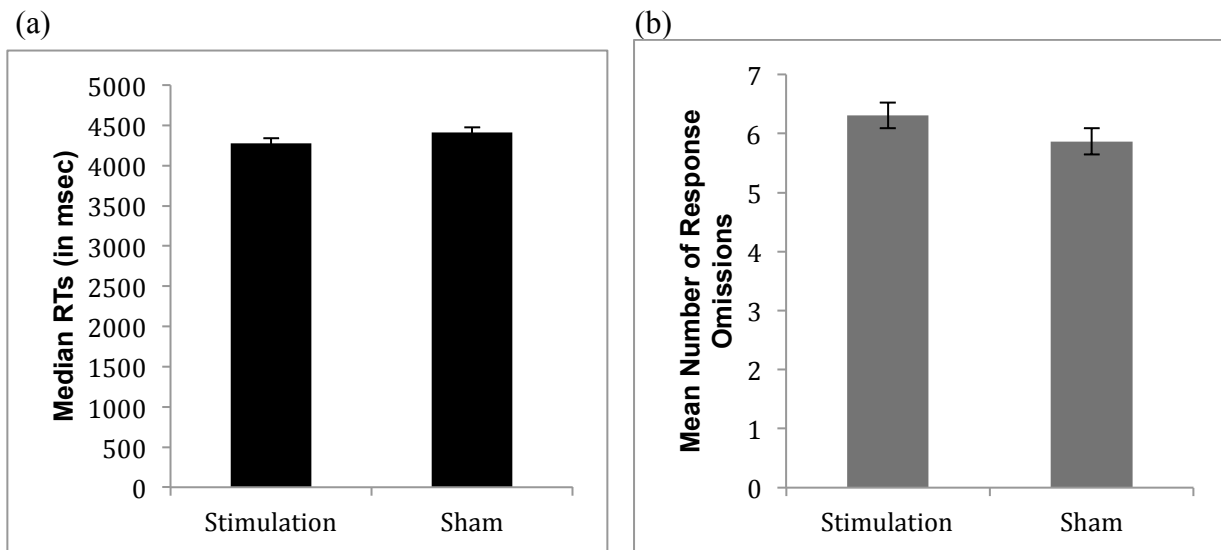
**Figure 7.** Effects of task order within the conjunctive condition in probability judgments of blocks D, E, and F.

### *Uncommon Uses*

All analysis was conducted based off of that of Chrysikou (2013) experiment, see Figure 8. Participant responses were transcribed from the video recording and reaction times were extracted from the E-Prime data file. Individual responses were omitted if there was no answer provided, the microphone failed to register a reaction time, or if the response violated the instructions and if the number of total response omissions exceeded fifteen for any participant

then the participant was dropped due to concern that the remaining reaction times were not representative. Out of the forty-two who participated, fourteen were dropped because microphone reaction time malfunction exceeded fifteen (4), no-responses exceeded fifteen (1), instruction violations exceeded fifteen (1), combined reaction time malfunctions, no-responses, or instruction violations exceeded fifteen (7), or because video was lost (1).

For the remaining twenty-eight participants, median reaction times were calculated for each. Median reaction times for those receiving stimulation ( $M = 4275.12$ ,  $SD = 1034.78$ ) were not significantly different from those receiving sham ( $M = 4411.12$ ,  $SD = 1136.65$ ,  $p = 0.414$ , one-tailed t-test). Number of omissions between stimulation ( $M = 6.3077$ ,  $SD = 2.9829$ ) vs. sham ( $M = 5.8667$ ,  $SD = 3.4614$ ) conditions was also compared, but there was no significant difference ( $p = 0.36088$ , one-tailed t-test).



**Figure 8.** Performance on the uncommon uses task. (a) Median reaction times of participants by stimulation condition. Error bars indicate the standard of the mean for each condition. (b) Mean number of responses omitted per stimulation condition.

## Discussion

We used cathodal tDCS to examine its effect on causal learning. Previous work in developmental psychology and computational research reveals a difference between children and adults in the level to which they are sensitive to causal data that may contradict a currently held bias (Lucas et al., 2014). In such a situation, children can be considered better at learning from the evidence, since they are more willing to endorse an unusual hypothesis when inferring the causal relations between novel objects. Analogous research from cognitive neuroscience points to the prefrontal cortex as a critical location in cognitive control – essentially acting as a filter for the programmed retrieval of information. While beneficial for many aspects of life, the literature suggests that a relative hypofrontality (by a variety of means – underdevelopment, lesion, or neurostimulation) can result in more creative, less inhibited cognition.

In drawing a parallel between these two veins of research, we hypothesized that using cathodal tDCS to dampen activity in the left VLPFC would result in adults being more likely to endorse an unusual causal structure, as children do. Although the initial data reported here are still preliminary, results already suggest that adults may indeed experience a change in their pattern of hypothesis endorsement following cathodal stimulation.

As expected, there was no difference across stimulation conditions for the more common disjunctive causal learning condition. Both participants who received stimulation or sham correctly judged block F as a blicket while D and E were not, as supported by the training evidence. This result supports previous conclusions of the Lucas et al. (2014) experiment in which adults and children did not show significant differences in the disjunctive structure. The disjunctive relation is naturally a more common form of causation, so adults are unsurprisingly willing to use that structure to infer the structure of novel objects – the training evidence agrees

if not strengthens a currently held bias. We did not expect stimulation to have an effect in the disjunctive condition because there is no conflict between the structure supported by the evidence and the bias impinging on adult cognition. Therefore, a decrease in cognitive inhibition by means of cathodal tDCS would not help encourage an endorsement of an unlikely hypothesis among competing options because there is no such competition.

Training evidence in the more unusual conjunctive causal structure, on the other hand, can have more manifold outcomes when inferring relationships of novel objects. As seen in the Lucas et al. (2014) paper, if children were trained with conjunctive evidence, they then appropriately used the conjunctive causal structure when making inferences about causal relations of novel objects, while adults did not. Here, we examined whether the cathodal tDCS would induce modest dampening of the VLPFC, reducing their bias, and allowing them to endorse the more unusual conjunctive causal structure, similarly to children.

In the conjunctive condition, results of the binary labeling show suggestive differences. Although the primary comparison between stimulation and sham on judgments of block D, while trending, were not yet significant. Beyond this primary question however, there were a few aspects of the data when comparing stimulation vs. sham in the conjunctive condition that were particularly promising. After observing the conjunctive evidence, those receiving stimulation did not judge F a blicket significantly more than block D, suggesting that participants were allocating causal power more evenly between blocks D and F, as the training evidence would support. In contrast, those receiving sham (and conjunctive training evidence), significantly differentiated D as not a blicket and F as a blicket, thus distinguishing in the causal power of D and F and more inline with a disjunctive rule. In the Lucas et al. (2014) experiment, adults significantly distinguished between the causal power of D and F, as those in the sham

condition are doing here. This implies that those receiving stimulation are in some ways holding blocks D and F as more similar in causal power than adults in previous literature or those receiving sham in this study.

In addition, of those participants receiving stimulation, those who had conjunctive training evidence were significantly more likely to endorse block D as a blicket than those who received disjunctive training evidence. Participants receiving sham on the other hand, did not significantly differ in labeling block D as a blicket between the conjunctive vs. disjunctive conditions. In the Lucas et al. (2014) paper, adults were in fact similar to the *stimulation* participants in this study, in that they had significantly different judgments of D between conjunctive and disjunctive conditions. Here, however, those receiving *sham* were even less likely than the adults in the Lucas et al. (2014) to be sensitive enough to the conjunctive training to significantly endorse D as a blicket in the conjunctive condition more than the disjunctive condition.

We introduced the probability measures in the current study in an effort to extract subtleties in reasoning that may be otherwise unattainable through the binary assignment measure. However, the probability measure did little to lend significance to a subtle difference in the area of interest: judgments about D between stimulation and sham conditions. Instead, in labeling D, those in stimulation and sham conditions became slightly more similar in their endorsement when asked about the probability compared to when labeling it a blicket or not a blicket. The binary labeling of blocks D, E, and F was conducted first in order to replicate the Lucas et al. (2014) procedure, and the probability measure was conducted after to avoid influencing binary choices, and enabling comparison with past results of Lucas et al. (2014). Because the binary question was first, the fact that the probabilities are *more* similar than the

categorization between stimulation and sham is surprising. Assigning probability after categorization was suspected, if anything, to result in an anchoring effect (e.g., Houston, Etling, Etling, & Brekke, 1996), but this was not borne out. This result has a variety of possible interpretations, but perhaps when faced with two competing answers (regarding judgment of block D) participants used the probability measure to mitigate their categorization in the opposite direction. For example, after labeling D not a blicket, one would give a probability of 2/10; or conversely, after labeling block D a blicket, one would assign it an 8/10.

The findings from the binary categorization data are also not present in the probability ratings. For participants receiving stimulation in the conjunctive condition, they did not judge D and F significantly differently in the binary question. However, in the probability measure there *was* a significant difference in those ratings: F had a significantly higher rating than D.

In the binary question, those receiving stimulation in the conjunctive condition judged D as a blicket significantly more than their counterparts in the disjunctive condition. Participants receiving sham did not show this effect. However, in the probability measure, both those receiving stimulation and those receiving sham differed significantly in their responses to D between conjunctive and disjunctive conditions. This result, while different from the binary data, aligns with the results from the Lucas et al. (2014) paper, which found adults to be somewhat sensitive to the conjunctive evidence. This more fine-grained probability measure suggests that both stimulation and sham participants are to some extent sensitive to the data, but those receiving cathodal stimulation are slightly more so.

In the final question of the causal learning experiment, participants were asked which of the blocks they should use to make the machine go. This question was created by Lucas et al. (2014) to ensure that participants were indeed reasoning about the causal structure and results



were not due to differences in interpretation of the questions regarding blickets. In the Lucas et al. (2014) paper, children and adults performed very differently in the conjunctive conditions: children chose options containing D as well as options containing multiple objects significantly more, while adults did not. Instead, adults chose to activate the machine with F alone regardless of condition.

Results from this experiment, interestingly, show that both participants in the stimulation condition and the sham condition chose F alone vs. choices containing D in almost equivalent numbers. This result lies somewhere in the middle of the choices of adults and children in the Lucas et al. (2014) paper. While this could be an encouraging difference for those receiving stimulation, it is less explicable for those in the sham condition. However with the current sample size (at  $n = 11$  for stimulation conjunctive, and  $n = 11$  sham conjunctive), there should be further investigation with an increased number of participants.

The causal learning task and the uncommon uses task was counterbalanced, and afterward, analyses were done to assess the possibility of order effects. Out of the participants in the conjunctive condition, those who participated in the uncommon uses task gave block D a significantly higher blicket probability rating than those who participated in the causal learning task first – regardless of stimulation condition. While this is the only significant result of the ordering effects, it suggests that there is at least a small effect present. Initial speculation was that the uncommon uses task could be priming adults to think more creatively, thus affecting their willingness to endorse a more unusual hypothesis. Another possibility is that under the parameters of stimulation, the tDCS increased its effects over the course of the experiment. In order to duplicate parameters used in Chrysikou et al. (2013), ninety seconds (including ramp up) was allotted prior to beginning the tasks. However, other research suggests that effects the

tDCS current can take three to five minutes to take full effect (Nitsche & Paulus, 2000). For this reason, it is possible that of those receiving cathodal stimulation, those who participated in the causal learning task first may have had differing strengths of stimulation.

In order to address this finding, further research will look into the possibility that greatest stimulation effects are seen after five minutes. In order to do this, a control experiment can be performed in which participants first perform the uses task, but unlike the current study, they either produce uncommon uses or they produces common uses for the objects, followed by the causal learning task. Thus, all causal learning tasks would take place over five minutes into stimulation, and we could differentiate between causal learning responses in those participating in the common vs. uncommon uses task first. Similar causal learning results between the conditions would suggest that the previous differences in stimulation strength over time might have led to differences in effect and therefore responses. Alternatively, differences between those producing common uses and those producing uncommon uses would suggest a possible priming effect of generating uncommon uses prior to the causal learning task.

This study failed to replicate the uncommon uses findings of Chrysikou et al (2013). While this is a puzzling result, the data collected was relatively messy, leading to fourteen out of forty-two participants being dropped from the analysis (primarily from a combination of no-response answers and failure of the microphone to record the response). The median reaction times were averaged for each participant, and both stimulation and sham conditions were *between* the reaction times of stimulation vs. sham participants in the Chrysikou et al. (2013). In this study, number of omissions was approximately six, while in Chrysikou et al. (2013), stimulation omissions were just under eight, and sham omissions just exceeded thirteen. This

suggests that perhaps there was a difference in coder's qualitative judgments of which answers merited omission. In future iterations of this study, special care will be paid to the set up of the microphone to ensure higher fidelity of recordings. Furthermore, perhaps a third coder can be involved in making the qualitative judgments regarding responses to be omitted.

The forward digit span, did, however replicate the findings of Chrysikou et al. (2013), ensuring that stimulation did not target cognition more broadly, but instead took effects rather selectively –on aspects of reasoning and cognitive control.

Taken together, these results contribute to research investigating learning biases in adults and the role of prefrontal cortex. Specifically, they shed light on the possible neural mechanisms that underlie Bayesian learning and selection amongst multiple hypotheses.

Gopnik, Griffiths, & Lucas (2015) discuss a possible reason for the learning differences between children and adults who demonstrate less flexibility with age. They suggest that hypothesis search is analogous to temperatures in that during “high temperature” searches, learners move frequently and easily between hypotheses with little commitment to a single hypothesis. Conversely, in “low temperature” searches, learners are more likely to settle on a hypothesis. While in the low temperature search, learners risk the possibility of missing a *better* hypothesis, they are able to quickly find one that is sufficient (Gopnik, Griffiths, & Lucas, 2015). Furthermore, Gopnik, Griffiths, & Lucas (2015) suggest that a phenomenon of “simulated annealing” occurs over development in which children perform hot temperature searches, and gradually “cool off” as they develop into adulthood.

The current study supports such an idea of simulated annealing. Results here, although preliminary, point toward an increased willingness of adults to endorse a more unusual causal

structure. This implies that the prefrontal cortex is indeed exerting a control mechanism over aspects of learning, i.e. the “cooling” effect on hypothesis search as seen in adults. This work also aligns with previous work regarding cognitive control (e.g., Thompson-Schill, Ramscar, & Chrysikou, 2009), which provided earlier evidence for the idea of annealing.

Thus, if further iterations continue to demonstrate that cathodal tDCS produces an alleviation of adult bias, this evidence will contribute to an explanation of why adults favor hypotheses that are common (correct in most cases), but can miss the more unusual hypotheses when they in fact are correct.

Results of the current study as well as the idea of annealing, work to bridge concepts of learning biases (a product of computational approaches) and cognitive control (studied in cognitive neuroscience). This analogy and increasing evidence for a connection between the exertion of cognitive control and the presence of learning biases opens up possibilities to apply knowledge of one idea to the other. Here, we see that the hypotheses selection taking place in cognition is likely shaped by the development of cognitive control by means of prefrontal maturation.

TDCS is a relatively new method with both favorable (e.g., Boggio et al., 2006; Jacobson & Lavidor, 2011; Chi & Snyder, 2011; Javadi & Walsh, 2012; Chrysikou et al., 2013) and doubtful (e.g., Horvath, Forte, & Carter, 2015) reviews of its efficacy. In this experiment, we acknowledge that any differences that the cathodal stimulation may give rise to will be subtle, and for this reason hope to continue data collection in order to make stronger claims with a larger sample size. In future iterations, we will hope to address possible ordering effects by utilizing the common uses task as a control to possible priming effects. This will allow us to deduce whether the small order effect of this study was due to priming or variable strength of the tDCS effects.

We also hope to address the failure to replicate the uncommon uses task through means of continued data collection and close attention to the coding.

### **Conclusion**

In summary, the results of this study show that cathodal tDCS may indeed have subtle effects in adults' willingness to endorse more unlikely hypotheses in causal learning paradigms. These results have important implications for the contributions of the prefrontal cortex in learning changes between children and adults, and suggest an important analogy between notions of cognitive control and developed learning biases. Specifically, these results provide preliminary support of the annealing hypothesis proposed by Gopnik, Griffiths, & Lucas (2015), pointing toward the prefrontal cortex as the neural mechanism responsible for hypothesis search changes over development. In future iterations, we hope to strengthen these findings with a larger sample size and continue to investigate the nature and extent of our current findings.

### **Author Note**

Thank you to Caren Walker, Alison Gopnik, Rich Ivry, and Lila Chrysikou for continued mentorship and contributions to the project. Thanks to Ludovica Labruna for instruction in using the tDCS equipment, and Elizabeth Kon for blind coding the Uncommon Uses responses.

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## Appendix

### Uncommon Uses Instructions

- The second task is about the organization of people's knowledge, in particular, about the use of objects. During the task, we will ask you to answer a quick question about a set of everyday items.
- This task will be conducted on the computer. During the session, you will see a series of object pictures appearing on the computer screen and your task will be to generate verbally a use for each object.
- Specifically, we will ask you to come up with an uncommon use for the object; this can be as crazy as you want it to be, so don't censor yourself in any way; it could be something that you've never seen or done before, but crossed your mind throughout the experiment, or you may have seen it maybe once or twice in your life. Here we are looking for something plausible, which yet deviates significantly both from the common and common alternative uses for the object (e.g., if you are packing a box and you are out of stuffing materials, you can use Kleenex tissues to stuff the box). Note that we are looking for uses that are object-specific and that would not be applied to any object (e.g., 'you can throw it to the ocean' or 'you can give it to aliens'). Also try to keep your responses short and follow the infinitive; for instance, 'to [verb] this' e.g., 'to stuff a box' and so on.
- Please try to avoid giving the same answer for multiple objects
- Please, try to answer the questions as fast as you can.
- Note that it may be easier to generate uses for some items relative to others. We understand that this may be a hard task at times, so if you cannot come up with an answer don't be discouraged; do the best you can. The program is set up in such a way so that it will keep on going regardless of whether you give a response or not, but – obviously – try to avoid not giving responses as much as you can.
- If, for some reason, you cannot come up with an answer we ask you to remain silent as opposed to saying things like "I don't know," "I have no idea." "hmm" and so on – point being we don't want the microphone to record anything as your response, if you don't have an answer to give.
- Also, try to avoid thinking aloud (e.g., "Kleenex tissues, Kleenex tissues, what can I do with Kleenex tissues") or starting your response before you have it (e.g., "You could.....").
- Before we begin, I will put up a mini-version of the experiment, a training session, so that we can give you an idea of what the whole thing looks like, as well as the opportunity to ask any questions if you have.
- The actual task lasts about 10 minutes.
- You will not need to hit any buttons.
- A microphone will be used to record your responses.
- Watch for your voice dropping as you become involved in the task (we want to make sure that our microphone will pick up your voice without problems).
- Please, make sure that you answer the questions as fast as you can.

## Causal Learning Task Script

Today's study is an experiment we also run with children, so I appreciate your patience with the structure of the experiment and the language used. When I ask questions, you can record your answers in the packet. You may change your answers while we are still on a particular section, but once we've moved on and you've turned the page in your answer booklet, you may not go back to look at or change your previous answers. In this game, we are going to try to figure out which of these things I have here are blickets [*experimenter pulls out a bucket of objects*]. You cannot tell that something is a blicket just by looking at it, but they do have something called blicketness inside of them. Luckily I brought my machine here, and you know what's special about my machine? *Blicketness* makes my machine play music!

### Training 1:

Hmm, let's try three things first. [*Experimenter shuffles in bucket*]. Let's try this one, this one, and this one [*Experimenter pulls out three objects*]. It's important to figure out which ones are blickets! Let's call this one     A1    , this one     B1    , and this one     C1    . Let's see what happens when we put

A1	on the machine.	It did not turn on! (AND) / It turned on! (OR)
B1	“	It did not turn on!
C1	“	It did not turn on! (AND) / It turned on! (OR)
A1 and B1	“	It did not turn on! (AND) / It turned on! (OR)
A1 and C1	“	It turned on!
B1 and C1	“	It did not turn on! (AND) / It turned on! (OR)

Ok! Now I have questions for you. You can turn the page of your answer booklet, write down the name of the item, and circle your choice.

Do you think     A1     is a Blicket or not a Blicket?

“	B1	“
“	C1	“

You may take as long as you like and when you are ready to move on, please turn the page in your answer booklet.]

### Training 2:

Now, let's try three things first. [*Experimenter shuffles in bucket*]. Let's try this one, this one, and this one [*Experimenter pulls out three objects*]. It's important to figure out which ones are blickets! Let's call this one     A2    , this one     B2    , and this one     C2    . Let's see what happens when we put

A2	on the machine.	It did not turn on! (AND) / It turned on! (OR)
B2	“	It did not turn on!
C2	“	It did not turn on! (AND) / It turned on! (OR)
A2 and B2	“	It did not turn on! (AND) / It turned on! (OR)
A2 and C2	“	It turned on!
B2 and C2	“	It did not turn on! (AND) / It turned on! (OR)

Ok! Now I have questions for you. You can turn the page of your answer booklet, write down the name of the item, and circle your choice.

Do you think A2 is a Blicket or not a Blicket?  
 “ B2 “  
 “ C2 “

You may take as long as you like and when you are ready to move on, please turn the page in your answer booklet.

### Test

Now, let's try three things first. [*Experimenter shuffles in bucket*]. Let's try this one, this one, and this one [*Experimenter pulls out three objects*]. It's important to figure out which ones are blickets! Let's call this [D], this one [E], and this one [F]. Let's see what happens when we put

D on the machine. It did not turn on!  
 D “ It did not turn on!  
 D “ It did not turn on!  
 E “ It did not turn on!  
 D and F “ It turned on!  
 D, E and F “ It turned on!  
 D and F “ It turned on!

Ok! Now I have questions for you. You can turn the page of your answer booklet, write down the name of the item, and circle your choice.

Do you think D is a Blicket or not a Blicket?  
 “ E “  
 “ F “

You may take as long as you like and when you are ready to move on, please turn the page in your answer booklet.

### Probability

Now on the page in front of you, please write down the name of the item, and indicate the probability that it is a blicket on a scale of 0-10. Zero means that you are absolutely certain the object is not a blicket, five means it is equally likely to be a blicket or not a blicket, and ten means that you are absolutely certain the object is a blicket.

What is the probability that D1 is a Blicket?  
 “ E1 “  
 “ F1 “

You may take as long as you like, and when you are ready to move in, please turn the page in your answer booklet.

### Intervention

Great! Now, which of these should we use to make my machine turn on?

You may turn to the next page in your answer booklet and write your answers in the box provided. You may take as long as you like. Please close your answer booklet when you are done. [*If participants ask whether or not they can choose more than one item, Experimenter tells them to go with their instinct or their best guess*].

**Forward Digit Span Instructions**

The third task is a brief memory task. I will be reading sequences of numbers to you and your task is to repeat them back to me in the same order. I will be reading the numbers at approximately one number per second, but you can repeat them back as fast as you want. For example, I will say something like “1,2,3” and you will say: ... Note that in the beginning this will be easy; progressively the task gets harder as the sequences of numbers get longer, so do the best you can. Do you have any questions?