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Categorization is modulated by transcranial direct current stimulation over left prefrontal cortex

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ABSTRACT

Humans have an unparalleled ability to represent objects as members of multiple categories. A given object, such as a pillow may be—depending on current task demands—represented as an instance of something that is soft, as something that contains feathers, as something that is found in bedrooms, or something that is larger than a toaster. This type of processing requires the individual to dynamically highlight task-relevant properties and abstract over or suppress object properties that, although salient, are not relevant to the task at hand. Neuroimaging and neuropsychological evidence suggests that this ability may depend on cognitive control processes associated with the left inferior prefrontal gyrus. Here, we show that stimulating the left inferior frontal cortex using transcranial direct current stimulation alters performance of healthy subjects on a simple categorization task. Our task required subjects to select pictures matching a description, e.g., "click on all the ROUND THINGS." Cathodal stimulation led to poorer performance on classification trials requiring attention to specific dimensions such as color or shape as opposed to trials that required selecting items belonging to a more thematic category such as OBJECTS THAT HOLD WATER. A polarity reversal (anodal stimulation) lowered the threshold for selecting items that were more weakly associated with the target category. These results illustrate the role of frontally-mediated control processes in categorization and suggest potential interactions between categorization, cognitive control, and language.

1. Introduction

In trying to explain human behavior, scientists are attempting to explain one of the most flexible computational systems known. Presented with the scene shown in Fig. 1, humans can attend to and group together the buildings, the vehicles, the bicyclists, the pedestrians, or every green thing. Humans can also focus in on the diagnostic attributes to locate the single taxi, categorize the vehicles as sedans, buses, or SUVs, or group together all the motor vehicles, temporarily overlooking their differences. A traffic reporter might ignore almost all perceptual detail, describing the scene as "3rd avenue heading north is closed to car traffic." The same system can perform any of these tasks in well under a second.

These feats are made possible by categorization—a cognitive act that we define here as forming a representation of a stimulus for current task demands. Categorization allows an organism to enact a common response to perceivably different stimuli. This common response may be verbal—giving two objects[1] the same name—or nonverbal,

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[1] We use the term "objects" here because the experiments described all use concrete objects, but our reasoning applies equally, and perhaps more strongly, to other entities: verbs, abstract nouns, and relational categories.

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such as pointing to or selecting all the objects that are members of a given category. Given a simple category prompt such as FRUITS, humans have the ability to rapidly represent a scene in front of them in terms of category targets (the fruits) and everything else. As argued by Barsalou (1983, 1987), this ability is not limited to categories well established in memory, but extends to what are variously called ad hoc, goal-derived, or functional categories such as THINGS TO SELL AT A GARAGE SALE.

One proposal is that a critical component of categorization—the selection of properties relevant for current task demands—benefits from the regulatory functions of prefrontal cortex, particularly the left inferior frontal gyrus (LIFG). If true, then modulating neural activity in LIFG may affect categorization performance. Here, we examine this process of categorical representation in human participants by using transcranial direct current stimulation (tDCS), a noninvasive electrical stimulation technique that can temporarily affect cortical activity. It should be noted that the goal of the present work is not to make any claims about the role of specific brain regions in the categorization process, nor to make inferences regarding specific functions of the LIFG. Rather, is to test a set of predictions stemming from a particular way of conceptualizing the categorization process—that of highlighting task relevant dimensions and abstracting over task-irrelevant ones.

2. Category dimensionality and the role of cognitive control

To say that members of a given category are invariant in some way is to say that there is a behaviorally relevant dimension along which these entities are similar—similar enough to be interchangeable in at least one context.[2] For example, despite their obvious differences, a lime and a grasshopper are both reasonable instances of the category THINGS THAT ARE GREEN. Mashed potatoes and BBQ ribs are both quite decent members of a THINGS THAT ARE EDIBLE category. On our view, such acts of categorization involve selectively representing the dimension or set of dimensions that are shared by and are diagnostic of the category. So, in the case of the category THINGS THAT ARE GREEN the task-relevant dimension is color. At the same time, categorizing may involve some degree of abstraction over dimensions that are not predictive of the category in question. For example, in classifying an object as green, its ability to jump—present for grasshoppers, not so much for limes—is (temporarily) abstracted over.

Fig. 1. Humans are remarkably adept at categorizing items on multiple scales of abstraction in complex scenes such as this. Picture taken by first author.

It is useful to consider categorization acts as existing on a continuum (Pothos, 2005; cf. Lupyan & Vallabha, 2005). On one end are categorizations that can be made on the basis of a single or a small set of dimensions. For example, items in a THINGS THAT ARE GREEN category share color (to some degree at least), but not shape, size, material, etc. Such categories are sometimes said to be rule-based (Ashby, Maddox, & Bohil, 2002; Waldron & Ashby, 2001) and their formation is thought to require selective (or "controlled") activation of the task-relevant dimension and possibly inhibition of task-irrelevant dimensions, particularly when task-irrelevant dimensions are perceptually salient (see O'Reilly, Noelle, Braver, & Cohen, 2002 for a computational model; see Eimer & Kiss, 2010; Eimer & Kiss, 2011 for examples of this process in the domain of visual selection). Sloutsky and colleagues refer to such categories (and the corresponding process of categorization) as selection-based (Sloutsky, 2010). In this paper we call categories requiring such controlled activation *low-dimensional.*

The process of controlled activation has been linked to the left inferior frontal gyrus (LIFG) including the region often referred to as Broca's Area. For example, Thompson-Schill, D'Esposito, & Kan, (1999) had subjects generate either the color or an action of visually presented words. Priming the task-irrelevant property (e.g., color on an action-generation trial) led to increased LIFG activation as measured by fMRI (see also Badre & Wagner, 2005). The process of selective activation of conceptual information has been compared to that of visual selective attention (Kan & Thompson-Schill, 2004).

At the other end of the categorization continuum are categories containing items which may share many properties, but for which no single property determines cate-

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[2] Interchangeable does not mean indistinguishable. Imagine two categories: things weighing more than 4 grams and things weighing less than 4 grams. Clearly, if it is impossible to distinguish between something weighing.010 g and .011 g, no categorization effort is required to group them together. An act of categorization can, however, reduce the ability to perceive differences between entities placed in the same category. This is the well-described phenomenon of categorical perception (Goldstone, Lippa, & Shiffrin, 2001; Harnad, 1987). What is often under-appreciated is that categorical perception effects are quantitative in nature. It is virtually never the case that placing items into the same category renders previously distinguishable items indistinguishable(McMurray, Aslin, Tanenhaus, Spivey, & Subik, 2008; e.g., see McMurray & Spivey, 2000 for the argument against invariance within phonemic categories). A simple argument for why within-category representational collapse does not occur is that it is disastrously maladaptive. All entities need to be categorized in multiple ways, depending on current goals, and one normally has multiple goals. For example, given the goal of word-identification from speech, all differences between productions of a given word should be collapsed by the word recognition process. A task calling for word identification and nothing else may produce *some* abstraction over properties of the speech stream that are less relevant for word identification. But entirely collapsing differences over these properties would make it impossible to use the speech signal to recover speaker identity, emotional and prosodic content, etc. The alternative, that there are distinct parallel representations for every conceivable task which the organism might enact, is untenable.

gory membership. Consider a goal-derived or ad hoc category such as THINGS TO TAKE WITH YOU ON A PICNIC (Barsalou, 1983). Such a category does not lend itself to judgments based on any simple set of dimensions. An effective way to list members from such a category is to activate a schema or "semantic field." In this paper we call such categories *high-dimensional*. In general, forming a representation that distinguishes members of such a category from non-members relies on global associations and general semantic knowledge. We believe that common taxonomic categories such as BIRDS are also best viewed as high-dimensional, albeit to a lesser degree than the kinds of goal-derived categories described by Barsalou. The reason is that taxonomic categories generally cohere on numerous dimensions and have rich inter-feature correlations. A stimulus that activates a constellation of features that tend to occur with birds (has-feathers, has-two-legs, has-wings, etc.) is likely to be classified (correctly) as a bird. Such categories therefore possess higher inter-item relatedness (or "coherent covariation" Rogers & McClelland, 2004) than low-dimensional categories because, by definition, low-dimensional categories comprise items with one or few dimensions in common (see also Sloutsky's (2010) discussion of sparse vs. dense categories making a similar point). However, in contrast to low-dimensional categories, it is unlikely that activating any single feature of a taxonomically-based category would be sufficient. For example, activating "has-wings" would not enable reliable discrimination between birds and non-birds.

While relying on inter-item associations is useful in classifying items from high-dimensional categories, such associations may need to be actively suppressed when classifying items from low-dimensional categories. For example, consider a task in which subjects are presented with an array of color pictures and are prompted to identify all the pictures of green items. Successful identification requires that subjects to temporarily suppress the strong association between e.g., greenness and being a vegetable. Failing to do so may lead to a subject who selects the green vegetables, but fails to include grasshoppers, green umbrellas, and rotten oranges or, driven by the strong association between vegetables and greenness, fails to exclude a non-green vegetable such as a carrot. This relationship between category coherence/dimensionality and different needs for selection is schematized in Fig. 2.

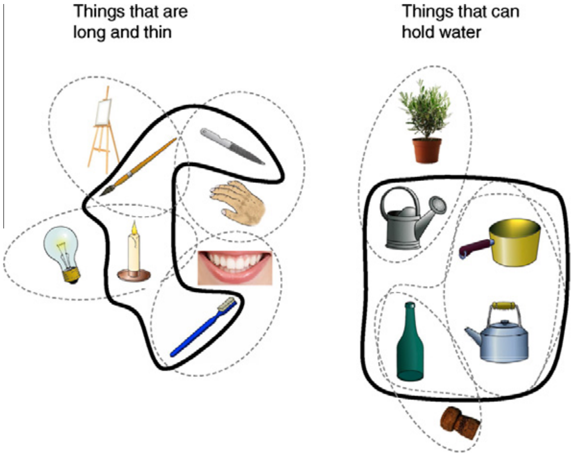

Fig. 2. A schematic illustration of category coherence. The left panel depicts a low-dimensional category, long and thin objects—perhaps the only attribute these objects have in common. Forming a representation of this category requires considerable cognitive control to include all the targets while simultaneously excluding semantically associated distractors. The right panel depicts a high-dimensional category, things that can hold water. In addition to the target category, at least some of the targets cohere in other ways: things found in kitchens, used in cooking, having a round shape, etc. As a result, the items cohere together, requiring less controlled activation to select the targets and exclude the distractors.

In sum, representing an object as a member of a low-dimensional category should require a greater degree of cognitive control to overcome the naturally low internal coherence between its category members. In contrast, because members of high-dimensional categories already cohere, forming a high-dimensional category requires less cognitive control (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Successful high-dimensional categorization does require activating the relevant semantic "field" (e.g., one needs to know about picnics to know what to take on one). However, because the targets of a high-dimensional category tend to overlap on numerous dimensions, they will effectively co-activate (prime) one another, hence requiring less controlled activation (see Sloutsky, 2010 for similar reasoning).

3. Transcranial direct current stimulation: A primer

Transcranial direct current stimulation (tDCS) is a non-invasive, painless method to change cortical excitability by using weak electrical currents applied to the scalp of the subject. The electrical currents from tDCS (approximately 1 mA on the scalp) are far too low to induce action potentials in cortical neurons and their effects on cortical excitability appear to stem from a change in spontaneous firing due to changes in the transmembrane potential (Iyer et al., 2005; Nitsche & Paulus, 2000; Wagner et al., 2007). For example Nitsche and Paulus (2000) showed that tDCS can modulate the excitability of primary motor cortex by up to 40% as measured by the size of motor evoked potentials induced with transcranial magnetic stimulation. Similar results have been found for changes in excitability of visual cortex as measured by the likelihood of seeing TMS-evoked phosphenes following tDCS stimulation (Antal, Kincses, Nitsche, & Paulus, 2003). Importantly, the direction of the effect depends on the polarity of the stimulation. Cathodal stimulation tends to lower cortical excitability whereas anodal stimulation tends to increase it.

There have been relatively few studies using tDCS to investigate cognitive functioning. A number of studies suggest that tDCS stimulation over fronto-temporal regions affects performance on various language tasks. Flöel, Rösser, Michka, Knecht, and Breitenstein (2008) found that anodal tDCS stimulation over Wernicke's area improved performance in a novel word-learning task.[3] Cathodal stimulation

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[3] Because tDCS stimulation extends over a relatively large area, we describe tDCS stimulation as being "over" a particular area rather than being "of" the area.

had no effect. Sparing, Dafotakis, Meister, Thirugnanasambandam, and Fink (2008) found that picture naming RTs were slightly decreased in normal subjects during anodal stimulation over Wernicke's area. Finally, de Vries and colleagues (2010) found that anodal stimulation over Broca's Area (left BA 44/45) improved the learning of an artificial grammar.

Most relevant to the present work are several studies showing that stimulation over left prefrontal cortex affects tasks associated with high levels of cognitive control. Iyer and colleagues (Iyer et al., 2005) found that anodal stimulation over left prefrontal cortex in healthy subjects improved verbal fluency, as measured by the number of words generated to a target letter in 90 s. Gordon and colleagues further explored stimulation over left prefrontal cortex on automatic and controlled verbal generation (2010). They found that during anodal stimulation subjects produced both more semantic clusters and a greater percentage of words within clusters on letter-cued fluency tasks. Cathodal stimulation tended to have the opposite pattern relative to controls. Several studies have examined effects of tDCS on classification learning using a weather prediction task (Kincses, Antal, Nitsche, Bártfai, & Paulus, 2004) and a prototype distortion task (Ambrus et al., 2011). The findings were mixed: Kincses et al. (2004) reported a slight benefit of anodal stimulation over left prefrontal cortex on implicit learning. Ambrus et al. (2011) found that when presented with a prototype of a category pattern not seen during training, participants were more likely to reject it following both anodal and cathodal stimulation of the DLPFC. Finally, Cerruti and Schlaug (2009) reported a beneficial effect of anodal tDCS to left dorsolateral prefrontal cortex on the remote associates task (RAT). The RAT requires subjects to form non-obvious associations to solve insight-style problems—a task thought to require strong executive functioning due to the need to ignore misleading clues (Bowden & Jung-Beeman, 2003).

4. The present study

In the present study we sought to manipulate neural activity in left prefrontal cortex with mild electric stimulation and investigate the consequences of this stimulation on participants' ability to place items into low- and high-dimensional categories. If the left prefrontal cortex is involved in the categorization process, facilitating selective representation of task-relevant dimensions and/or suppressing the task-irrelevant dimensions, the categorization process may be augmented by stimulation of this cortical region. Insofar as cathodal stimulation over the prefrontal cortex *suppresses* cortical functioning, it would impair processes involved in representing the category-relevant features, affecting performance on low-dimensional categories. Insofar as anodal stimulation *increases* functioning of prefrontal cortex, it should have the opposite effect: category-relevant features may be represented more strongly, thereby lowering the threshold for accepting items as members of the category. Such a ''hyperactive'' categorization process may lead to a propensity to choose objects that are poorer examples of the target category (somewhat similar to the finding that anodal stimulation over LIFG resulted in increase in sensitivity to more remote word-associates, Cerruti & Schlaug, 2009).

4.1. Participants

Twenty undergraduate students (ages 19–22, 13 female) from the University of Pennsylvania were randomly assigned to the anodal and cathodal groups—ten participants per group. A screening form was used to ensure that the participants had no history of previous neurologic or psychiatric disease. Because of potential effects on neuronal excitability we screened out subjects who are taking SSRI antidepressants, anti-convulsants, anti-psychotic or sedative/hypnotic medications. An additional twenty participants (ages, 19–22, 18 females) served as a no-stimulation comparison group. The stimulus norming studies were conducted online using the University of Pennsylvania and University of Wisconsin-Madison participant pools. Participants in the tDCS conditions were paid; the others participated in exchange for course credit. Subjects gave informed consent as approved by the Institutional Review Boards of both the University of Pennsylvania and the University of Wisconsin-Madison.

4.2. Experimental procedure

Participants were tested individually and told that they would be seeing groups of pictures along with a category or property description, and that their task was to choose all of the pictures that matched the description by clicking on them with a mouse. Each trial began with a prompt informing the participants of the category criterion they should use. Participants then clicked the mouse to reveal a screen with a 4-row by 5-column array of color pictures on a white background. Because we were interested in participants' categorization abilities rather than their ability to remember the task, the criterion, e.g., THINGS THAT ARE GREEN, was prominently displayed above the pictures throughout the trial. Participants could select as many or as few pictures as they deemed appropriate. Clicking on an object caused a gray frame to appear around it marking it as selected. Clicking it again un-selected the object allowing participants to change their mind. There was no time limit; the trial was terminated when the participant clicked a large ''Done'' button at the bottom of the screen. Subjects completed three blocks of 40 trials.

4.3. Materials

The targets and distractors were drawn from 260 color drawings of common objects (Rossion & Pourtois, 2004). These stimuli were used to construct 34 separate categories, 17 low dimensional categories and 17 high-dimensional categories. The *low-dimensional* categories identified targets that cohered on the basis of one or few dimensions. For example, the targets in a THINGS THAT ARE BLUE trial could vary in shape, size, and semantic category. The one thing they had in common was that they were all blue. The *high-dimensional* categories comprised items that cohered on multiple dimensions, that is, were related to each other in multiple ways. High-dimensional trials included both role-governed/ad hoc categories such as NON-FOOD THINGS FOUND IN A KITCHEN, as well as "common" categories such as FRUIT. What separated both of these from low-dimensional categories was that there was no single dimension on which targets could be distinguished from non-targets. Two of these categories are shown in Fig. 2, highlighting the hypothesized differences in cognitive control their representation requires.

For each category we designated four pictures as targets, though participants were free to select as few or as many targets as they wished. For example the targets of the BODY PARTS category were *hand*, *leg*, *toe*, and *finger*. An item was constrained to be a designated target for only a single category, despite some items being sensible targets for multiple categories. For example, one of the items—a round drum—was a reasonable target for both a MUSICAL INSTRUMENT trial and a ROUND OBJECT trial, but we included it in only one of these (in this case, the INSTRUMENT trial). Items could appear as distractors on multiple trials. For more open-ended categories such as THINGS THAT ARE VERY LARGE the designated targets were all considerably larger in their real-world size than the non-target items.

Pictures serving as targets in the two trial types (*low-dimensional* vs. *high-dimensional*) did not differ in naming RTs, naming accuracy, name agreement, imageability, or familiarity, all Fs < 1 (see Rossion & Pourtois, 2004 for definitions of these measures). There was a reliable difference in visual complexity with targets in the *low-dimensional* trials having lower complexity than targets in the high-dimensional trials, $F(1,211) = 15.29$, $p < .0005$ (this effect was less reliable when we averaged visual complexity of the set of targets for each category, $F(1,32) = 3.73$, $p = .062$).

4.4. Norming: Item acceptability and inter-item relatedness

Because we used existing rather than artificially-created categories, it was important to quantify the differences in category structure. We therefore conducted several norming studies designed to measure characteristics of the materials we deemed relevant to the hypothesized differences in the degree of cognitive control required to perform the categorization.

The two primary measures derived from the norming studies were *item acceptability* and *inter-item relatedness*. To derive item acceptability, 41 additional participants were shown each of the target pictures plus pictures of items that were chosen on at least two occasions by participants during the main categorization task. Along with a picture was a text label containing the same criterion prompt shown to the participants of the categorization study. The picture-category criterion pairs were shown in random order. The full set contained 519 such pairs and each participant provided ratings for 170 distinct pairings. For each picture-category pair combination, raters were asked to respond to the question "How closely does the picture match the category/property?" on a 7-point Likert scale, 1:"Extremely Poorly"; 7:"Extremely Well". Participants were encouraged to use the entire scale. A mean acceptability rating for each category was computed by averaging across the acceptability ratings for its constituent targets.[4]

To derive inter-item relatedness, we recruited a new group of 16 participants. Each participant was shown the four 4 designated target images for each category (one category at a time), and prompted with the question "Considering all ways in which these items relate to each other, how similar are they?" Participants responded using a 5-point Likert scale, 1:" Completely different/nothing in common", 5: "Extremely similar/lots in common." Filler trials containing groups of four unrelated pictures were included to discourage participants from only using the upper end of the scale. After making a response using the Likert scale, participants were asked to indicate what, if anything, the four items had in common.

The two measures—acceptability and relatedness—were positively correlated, $r = .62$, $p < .0005$, (see Table 1) with the correspondence being much stronger for high-dimensional categories $r = .53$, $p = .023$ than for low-dimensional categories, $r = .16$, n.s. As shown in Fig. 3, acceptability and relatedness measure somewhat distinct aspects of the categories and their constituent targets.

Consider the category THINGS THAT ARE SOFT. It has a moderately high acceptability rating, meaning that its constituent targets were generally judged as being good category members. Yet, when judged together without the category prompt, the items were viewed as being barely related.[5] That is, without the category prompt, the items did not cohere. Consider now the category HOME APPLIANCES. This category has intermediate relatedness, but low acceptability.

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[4] Per request of one of the reviewers we also computed an additional set of similarity measures using a corpus derived measure of global semantic similarity. We used the freely-available 'DISCO' algorithm http://www.linguatools.de/disco/disco_en.html) trained on the English version of Wikipedia. Naturally, similarity here was computed over written words rather than images. We computed two sets of similarity measures: Within-category similarity was derived by averaging, for each of the category types in our main study, the pairwise similarity between the designated targets. For example, the within-category similarity of the 'things that are soft' category was the average of all the pairwise similarity ratings between the targets "bed", "rabbit", "mitten", and "cat." Between-category similarity was likewise defined as the average similarity between the targets of a particular category used in the experiment and all the distractors that were shown to the subjects. A Python script for performing these computations is available from the first author on request. The within-category similarity measure was reliably correlated with the relatedness measure we previously collected from human subjects ($r = .568$, $p < .0005$). Like the relatedness measure, it was also reliably lower for low-dimensional, compared to high-dimensional categories: $M_{\text{low-dim}} = .016$, $M_{\text{high-dim}} = .047$, $t(19) = 3.82$, $p = .001$. This makes sense: the targets from high-dimensional categories tend to co-occur in a larger range of contexts. The greater DISCO similarity between a dress and a skirt, for example (members of the high-dimensional category 'clothes') compared to a toothbrush and a pen (members of the category thin, long things) derives from the larger shared contexts of dress/skirt compared to toothbrush/pen. The between-category measure did not vary between low- and high-dimensional categories, $M_{\text{low-dim}} = .007$, $M_{\text{high-dim}} = .008$, $t < 1$. This is again not surprising given that the distractors were drawn from the very same set for all the categories. Although correlated with our relatedness measure, DISCO within-category similarity did not predict hit rates for any of the participant groups, ps > .7 and its inclusion in the regression did not qualitatively affect the reported results.

[5] Relatedness does not simply reflect the degree to which the common feature is obvious to the raters. For instance, although 15/16 raters indicated that the common property of items in the category THINGS THAT ARE ORANGE was that they were orange, this was insufficient to generate high relatedness.

Table 1
Correlations between norming variables.

	Acceptability of designated targets$^{\text{HD}}$	*Inter-item relatedness* of designated targets$^{\text{HD}}$	Number of unique responses to a text criterion$^{\text{LD}}$
Inter-item relatedness of designated targets$^{\text{HD}}$	.62 (<.0005)		
Number of unique responses to a text criterion$^{\text{LD}}$	−.54 (.001)	−.66 (<.0005)	
Acceptability of generated category members$^{\text{HD}}$	.56 (.001)	.35 (.04)	−.60 (<.0005)

Notes:
These correlations values are derived from the 34 unique category types used in the main categorization experiment. *HD* marks variables which had significantly higher mean values for categories designated as ‘high-dimensional’ than categories designated as low-dimensional; *LD* denotes the opposite. *Number of unique responses to a text criterion* refers to the number of unique responses the 10 participants produced to each of the 34 criteria. The minimum value is 5, obtained if all 10 participants produced the same 5 exemplars for a given category. The maximum value is 50, obtained if all 10 participants produced a different 5 exemplars for a given category. The actual values ranged from 23 to 37.
Acceptability of generated category members refers to the acceptability responses collected from the generated category exemplars in response to text-labels such as “A thing that is red.”

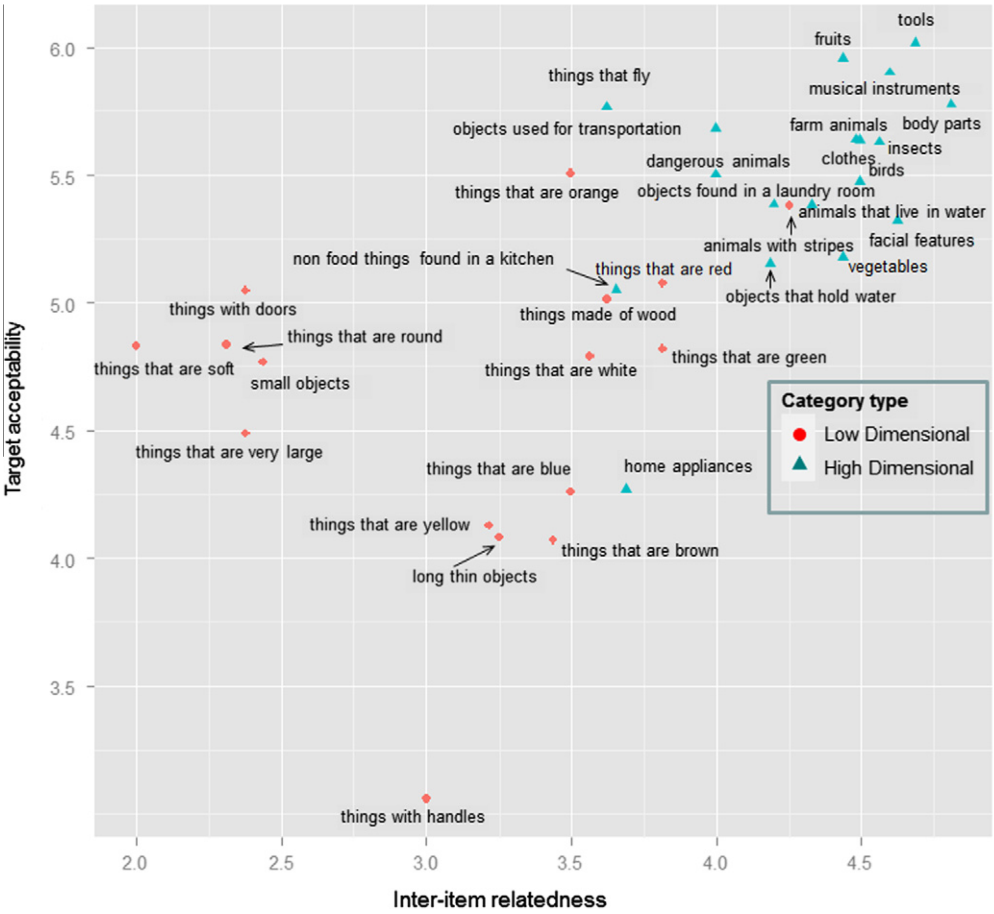

Fig. 3. Each category used in the study coded by type (high- vs. low-dimensional) and plotted by collected ratings of mean acceptability of designated targets and inter-item relatedness.

The items serving as targets cohere even without an explicit category prompt, but they are not viewed as particularly good instances of the category in question. Another way to think about these two measures is that *acceptability* measures how acceptable the pictures are of the externally provided category—how good is X as a member of category Y. *Relatedness* reflects the degree to which the pictures “propose” a grouping on their own through their mutually correlated features.

As evident in Fig. 3, *low-dimensional* categories tend to have lower relatedness, $F(1,32) = 39.92$, $p < .0005$, and have targets with lower average acceptability than *high-*

dimensional categories, $F(1,32) = 23.26$, $p < .0005$. Given the conceptual distinction between these measures combined with their high correlation, it is sensible to ask which of these measures predicts category type (low- vs. high-dimensional) when their common variance is partialed out. A logistic regression predicting type from both relatedness and acceptability indicated that relatedness continued to be a significant predictor, $Z = 2.07$, $p = .04$ while acceptability was no longer significant, $Z = .87$, $p = .39$. In other words, controlling for relatedness, targets of *high-dimensional* trials do not have greater acceptability than targets of *low-dimensional* trials. Controlling for acceptability, targets of high-dimensional trials, however, are more related to each other than are targets of low-relatedness trials.

These norming data suggest that categories that are defined on one or a few dimensions—low-dimensional categories—indeed tended to cohere less well than high-dimensional categories. Does this finding represent a real-world difference between low-dimensional and high-dimensional categories or simply an accident—an artifact of the targets we chose for the various categories? To find out, we conducted an additional generate-and-rate norming study. In the first part—generation—10 new participants were asked to generate five items for each of our 34 categories. We then compiled the unique responses and asked a separate group of 26 participants to rate the degree to which these were good members of the categories in question thereby producing a *de novo* measure of acceptability. For practical reasons of scale, only the items generated in positions 1–3 were included in the rating session. The final list of items to be rated contained 470 category-item combinations. None of the participants in these norming tasks participated in the main study.

Analysis of all the initially generated items revealed that low-dimensional categories contained significantly more unique responses ($M = 28.0$, $SD = 5.2$) than high-dimensional categories ($M = 18.8$, $SD = 4.41$), $F(1,32) = 30.69$, $p < .0005$. That is, participants tended to produce more similar responses when asked list items from a high-dimensional compared to a low-dimensional categories, lending further support to our position that categories designated as *high-dimensional* have greater internal coherence. We then correlated the acceptability measure for the generated targets with the original acceptability measure, described above. The two measures were strongly correlated, $r = .56$, $p = .001$. We present the full correlation matrix in Table 1. Note also the strong relationship between our original *relatedness* measure (derived using previously selected picture targets) and the number of items generated in response to the category prompts from the separately conducted norming study.

The strong convergence across independent norming studies and across picture and text stimuli suggest that measures such as acceptability and inter-item relatedness are measuring (however imprecisely) the internal structure of the category rather than simply reflecting our choice of materials, and that there is a principled difference in the structure of low- and high-dimensional categories (which, although we dichotomize here for descriptive simplicity, is best thought of as existing on a continuum, see Pothos, 2005).

4.5. Transcranial direct current stimulation procedure

Stimulation was delivered by a battery-driven constant DC current stimulator (Magstim Eldith 1 Channel DC Stimulator Plus). The rubber electrodes were inserted into saline-soaked 5 cm × 7 cm sponges. Electrode placement was made by reference to the 10–20 system. The stimulation electrode was placed on the F7 site, corresponding roughly to left inferior frontal cortex (subsuming Broca's Area) (Homan, Herman, & Purdy, 1987). The reference electrode was attached to the contralateral mastoid. At the start of each session the current was increased gradually over 30 s to 1.5 mA. Subjects tended to feel a tingling/itching sensation during stimulation onset. This sensation faded over ~15 s. This experience was consistent with previous reports (de Vries et al., 2010; Nitsche et al., 2003). Stimulation lasted for 20 min and began during the instruction portion of the experiment. Depending on the speed with which the participant responded, stimulation continued through the entire task or ended shortly before the end of the task.

4.6. Results

The main dependent variable was the proportion of targets chosen on each trial (hit rate). A secondary variable was the rate of selecting objects that were not designated as targets. We will use the term "non-target selection rate" rather than the familiar term "false alarm rate" because, as we discuss below, most of such selections were of items that could conceivably be included in the category, but tended to be marginal members relative to the designated targets).[6] We predicted that performance of the control group would lie between the two groups receiving tDCS, hence the first analysis we ran included an ordered factor predictor for the group as a between-subject variable, and trial-type as a within-subject factor.

Unless otherwise specified, all analyses are based on general linear models. Performance was reliably worse for low-dimensional than high-dimensional trials, $F(1,38) = 26.74$, $p < .0005$. The main effect of group was not significant, $F < 1$. Critically, the analysis showed that group significantly interacted with trial-type, indicating that the magnitude of the difference between the low- and high-dimensional trials was modulated by tDCS (with group modeled as a linear predictor to model for the hypothesized opposite effects of anodal and cathodal stimulation, $F(1,37) = 4.60$, $p = .039$ (Fig. 4). In a second analysis we repeated analysis for just the two tDCS groups. Trial-type was a highly reliable predictor of hit rates, $F(1,18) = 14.63$, $p = .001$, with poorer performance on the low-dimensional compared to high-dimensional trials. The overall performance of the two groups was not significantly different, $F < 1$. There was a reliable group by trial-

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[6] Analyses of RTs revealed a highly significant advantage for low-dimensional relative to high-dimensional trials in all three groups ($p < .0005$; $Med_{\text{low-dimensional}} = \sim 1000$ ms; $Med_{\text{high-dimensional}} = \sim 1200$ ms). There were no other group differences or interactions.

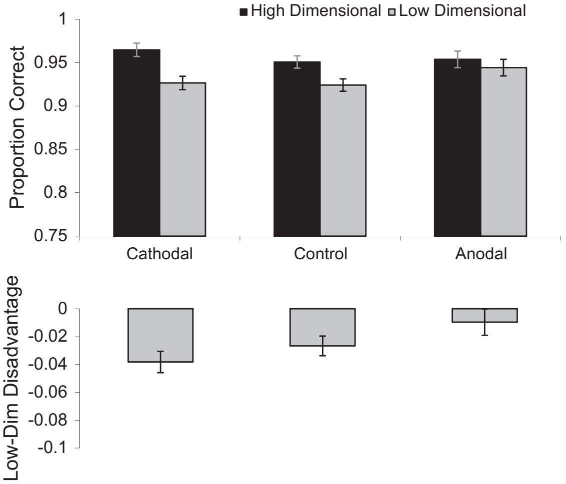

Fig. 4. Proportion of targets selected by the three experimental groups (top panel) and the difference between low- and high-dimensionality categories (bottom panel). Errors bars indicate ±1SE of the mean condition difference for each group.

type interaction, $F(1,18) = 5.11$, $p = .036$. As shown in Fig. 4, participants in the cathode group selected fewer correct targets on low-dimensional relative to high-dimensional trials, $F(1,9) = 23.40$, $p = .001$. Trial-type was not a significant predictor of performance in the anode group, $F(1,9) = 1.01$, $p = .341$.[7]

This initial analysis suggests that both types of stimulation affect performance, but in opposite directions. Cathodal stimulation appears to have increased the difference in performance between low-dimensional and high-dimensional trials and anodal stimulation appears to have decreased this difference.

5. Analysis of performance as a function of item acceptability and inter-item relatedness

Although control, anodal, and cathodal groups did not differ in overall hit rates, the cathode group, as we describe below, showed a distinct pattern of performance when target *acceptability* and *inter-item relatedness* were taken into account. To examine how performance was affected by *acceptability* and *relatedness* for the three groups (control, anodal-stimulation, and cathodal-stimulation), a linear model was constructed predicting hit rates for each category using acceptability, relatedness, group, and second-order interactions as predictors. Relatedness, (controlling for acceptability) was a reliable predictor of accuracy, $F(1,93) = 11.10$, $p = .001$; the contribution of acceptability controlling for relatedness was marginal, $F(1,93) = 3.53$, $p = .064$. Examination of group-by-relatedness and group-by-acceptability interactions revealed that the performance of the three groups was differentially modulated by acceptability, $F(2,93) = 4.73$, $p = .01$, but not by relatedness, $F(2,93) = 2.01$, $p = .14$.

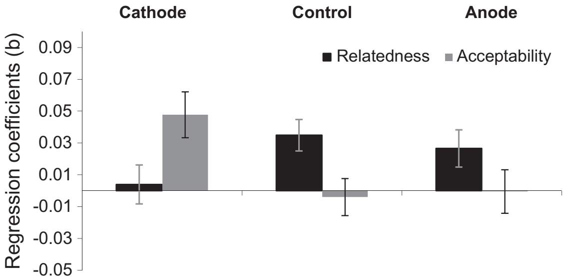

Fig. 5. Multiple regression coefficients for the three experimental groups. A positive coefficient indicates that categorization performance was positively correlated with the given dependent variable (inter-item relatedness and item acceptability). Errors bars indicate ±1SE of the mean.

Fig. 5 visualizes this relationship by plotting the regression coefficients of target-acceptability and inter-item relatedness predictors for the three groups. Performance of the cathodal group was more strongly modulated by acceptability than was that of the anode group, $F(1,62) = 5.89$, $p = .018$, and marginally more than the control group, $F(1,62) = 3.88$, $p = .053$. In other words, item acceptability strongly modulated performance of subjects receiving cathodal stimulation, $F(1,32) = 20.64$, $p < .0005$, but not subjects receiving anodal or no stimulation, $F < 1$.

Next, we examined which categories specifically were most impacted by cathodal and anodal stimulation. We computed difference scores between selections made by the cathode, anode, and control groups and attempted to predict these difference scores from relatedness and acceptability. This analysis is visualized in contour plots shown in Fig. 6. There were no systematic differences between the hit rates of the anode and control groups (and accordingly, the differences were not predicted by either relatedness or acceptability, $F < 1$). In contrast, the differences between the cathode and control groups were predicted by both acceptability, $F(1,30) = 12.03$, $p = .002$, and relatedness, $F(1,30) = 5.08$, $p = .032$. There was also a significant interaction between these predictors, $F(1,30) = 6.94$, $p = .013$. The two variables together accounted for 52.3% of the variance. The comparison between cathode and anode groups led to a similar (though noisier) pattern: the cathode group showed poorer performance for the categories having the lowest acceptability ratings controlling for relatedness, $F(1,30) = 6.46$, $p = .02$. Relatedness was a marginal predictor, $F(1,30) = 3.42$, $p = .07$. This analysis identified two categories having unusually high leverage and/or residuals (THINGS WITH HANDLES, and THINGS THAT ARE VERY LARGE). Removing these two categories rendered the interaction coefficient nonsignificant; all other results remained virtually unchanged.[8]

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[7] Despite our attempts to ensure that only the designated targets constituted good choices, analysis of the results revealed that a number of items not initially designated as targets were chosen on at least three occasions and, in a subsequently conducted norming task received ratings that were on par with designated targets. We therefore counted selections of these pictures as correct responses. None of our results change substantially when we restrict the analysis to only the originally designated targets.

[8] The same pattern is revealed if we conduct an analysis more resistant to outliers by constructing a binary dependent variable, set to 1 if cathodal performance is lower than control performance and to 0 otherwise—and performing a logistic regression with item acceptability inter-item relatedness as predictors.

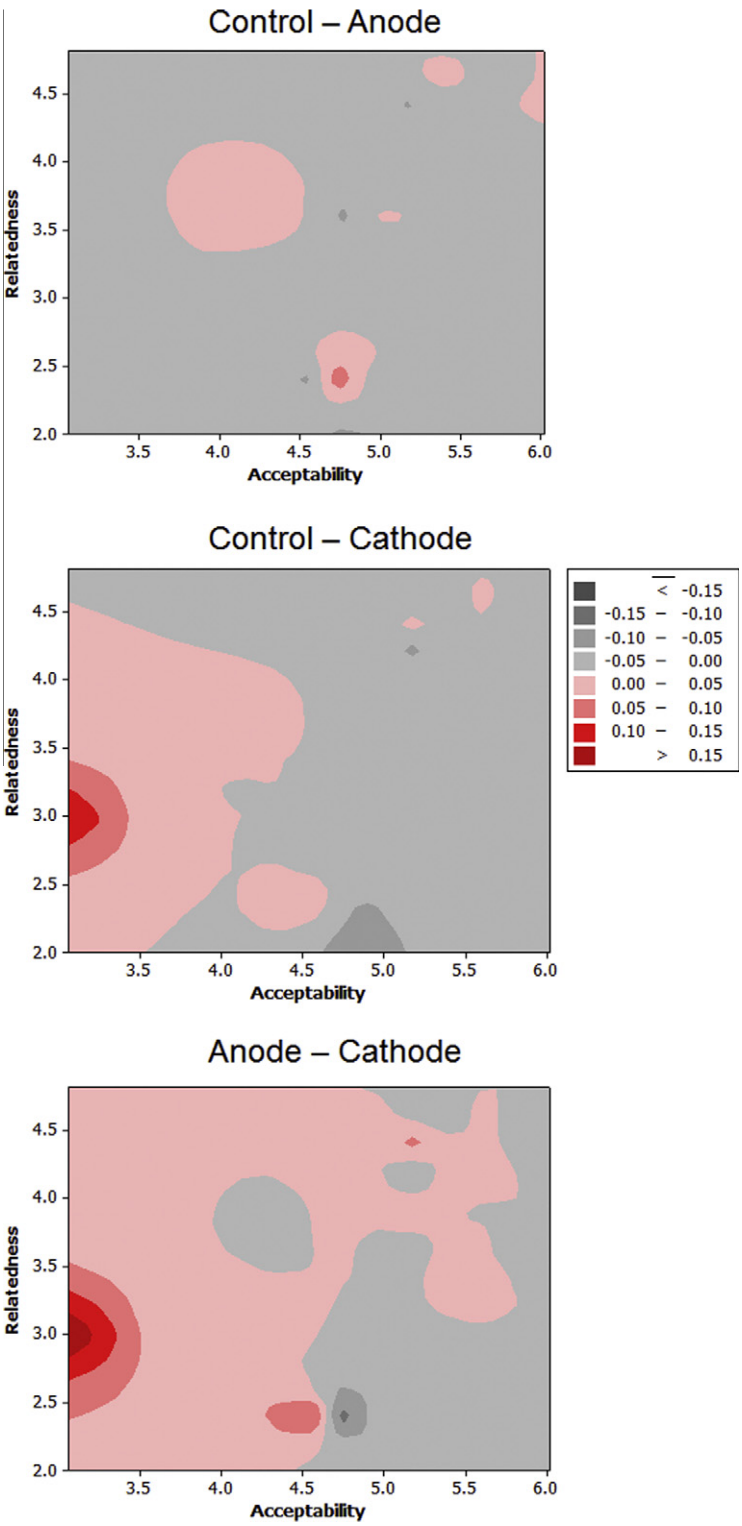

Fig. 6. Top: The difference in hit rates between control and the anode conditions as a function of mean target acceptability and inter-item relatedness. Middle: The difference between control and cathode-simulated group. Bottom: The difference between anode and cathode groups. The red color in the middle and bottom panels indicates acceptability/relatedness combinations for which the cathode group performs more poorly than the control group and than the anode group. The dark red area on the lower-left shows considerably poorer performance of the cathode group on the category of THINGS WITH HANDLES.

In combination, these analyses suggest that cathodal stimulation impacted performance most for categories having lower target-acceptability, particularly when the inter-item relatedness was low (the latter result is possibly an artifact of our materials and requires further testing).

5.1. Analysis of non-target selections

We next compared whether the participants in the anodal, cathodal, and control groups differed in their tendency to select exemplars that were not designated as targets by the experimenters. For example, for a trial that asked participants to choose "things that are soft," the designated targets were: bed, rabbit, mitten, and cat. However, there were other objects such as lips, coat, and strawberry which, depending on one's criterion, could conceivably be included in the category. In the first of two analyses, we treated such selections as non-target selections and examined whether the non-target selection rate differed among the three groups. A linear model using group (cathode, control, anode) as a linear predictor revealed a significant effect of group, $F(1,37) = 19.19$, $p < .0005$. A Tukey test with simultaneous 95% CIs confirmed that the anode group had significantly more non-target selections ($M = 12.3\%$) than the cathode group ($M = 7.8\%$) or the control group ($M = 8.8\%$). The cathode and control groups did not differ reliably.

We next examined whether this increase in non-target selections for the anodal group was specific to *low-dimensional* or *high-dimensional* trials. Subjects in all three groups had fewer non-target selections for high-dimensional relative to low-dimensional trials, $F(1,38) = 138.09$, $p < .0005$. For example, participants were more likely to extend the category of LONG, THIN OBJECTS beyond those designated as targets ($M = .140$) than the category BIRD ($M = .004$). For the cathode, control, and anode groups, the difference between non-target selections for the high-dimensional and low-dimensional trials was 5.5%, 6.0%, and 8.4%, respectively (a greater proportion of non-target selections for low-dimensional categories). A linear model using group as a linear predictor and trial-type as a binary predictor revealed a marginal group by trial-type interaction, $F(1,37) = 3.70$, $p = .062$. One of the anode group subjects was flagged as a statistical outlier (3.25 SDs away from the regression line); removing this subject greatly increased the reliability of this interaction, $F(1,36) = 9.29$, $p = .004$. This effect may be due to anodal stimulation increasing the non-target selection rate on the low-dimensional trials, or decreasing the non-target selection rate on high-dimensional trials. Analyzing the effect of anodal stimulation separately for the high- and low-dimensional categories supported the conclusion that anodal stimulation primarily increased non-target selections for the low-dimensional trials. For these, the group effect was highly reliable, $F(1,37) = 10.41$, $p = .003$ (anodal > cathodal = control). For the high-dimensional trials, anodal stimulation did not reliably increase non-target selections relative to the cathode and control groups, $F(1,37) = 1.25$, $p = .27$.

Whether a strawberry is soft is, to some degree, in the eye (or hand) of the beholder. We can alternatively examine whether the items selected by the anode group were deemed as less acceptable members of the category, as judged by a separate group of raters. Finding that participants select objects with lower acceptability ratings would indicate that they had a broader definition of what it meant to be a member of a given category. The three groups were reliably different from each other, $F(2,39) = 9.40$, $p = .001$. These differences arose from participants in the anode group selecting objects that on average had lower acceptability ratings ($M = 4.87$) than participants in the cathode ($M = 4.96$) and control groups ($M = 4.93$) (Tukey test with 95% CIs). The two latter groups were not reliably different, $F(1,29) = 2.61$, $p = .12$. Just as with the proportion of targets selected measure, the control group was numerically intermediate between the anode and cathode group.

Let us examine one category in detail as an illustration of the performance differences between the three groups. When asked to select "things that are soft," the cathode and anode group did not differ in the number of designated targets they identified: $M_{\text{cathode}} = 3.83$; $M_{\text{anode}} = 3.80$, $F < 1$. However, the anode group had a significantly higher non-target selection rate, $M_{\text{cathode}} = 23\%$; $M_{\text{anode}} = 38\%$, $F(1,19) = 5.53$, $p = .03$. For example, some participants in the anode group clicked on the following items as examples of things that are soft: lion (3/10), lips (3/10), goat (3/10), coat (3/10), strawberry (4/10), tomato (2/10). Although one can see how a coat or tomato can be judged as being soft, *none* of the participants in the cathode group clicked on any of these pictures. Among the controls 2/20 clicked on lion, 1/20 on lips, 1/20 on goat, 4/20 on coat, 0/20 on strawberry, 0/20 on tomato.

These results provide suggestive evidence that anodal stimulation lowers the threshold for accepting an item as a member of the prompted category, specifically for categories hypothesized to have higher cognitive-control requirement (low-dimensional trials). A plausible alternative (though one that this experiment was not designed to test explicitly) is that the anodal group's responses were simply more noisy or random. To tease these accounts apart we computed a trial-by-trial response incoherence score. The incoherence score of a response was increased by 1 anytime a participant chose an item with a lower acceptability rating than an item that was not selected. For example, on a "things that are soft" trial, choosing a lion (acceptability = 2.88), but not lips (acceptability = 4.00) would increase the incoherence metric by 1, reflecting a kind of noise in the categorization process. In contrast, choosing both lion and lips would not be indicative of greater noise, but rather a lower threshold for making a choice (as both lion and lips have lower acceptability than the designated targets). We found that performance on *low-dimensional* trials had significantly greater incoherence scores for all three groups (anode, cathode, control), $F(2,36) = 120.19$, $p < .0005$, but there were no group differences in this incoherence measure, ($M_{\text{control}} = .25$, $M_{\text{cathode}} = .24$, $M_{\text{anode}} = .23$), $F < 1$, and no reliable group by trial-type interaction, $F(2,36) = 1.30$, $p = .29$. Our measure of response incoherence is only one way of measuring noise in the categorization process and it is therefore difficult to make strong conclusions about the effect of tDCS on

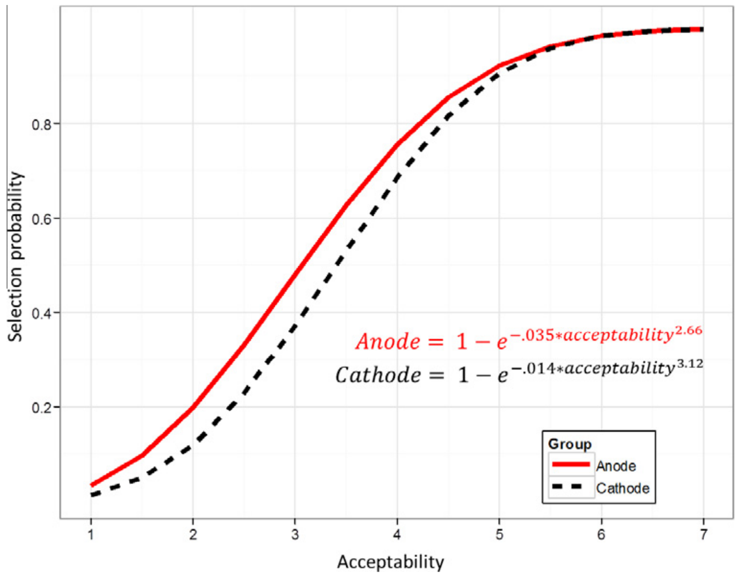

Fig. 7. The likelihood of selecting an item (either target or non-target) as a function of its rated acceptability.

this construct. The overall pattern of results, however, supports the interpretation that the greater level of non-target selections shown by the anode group reflects a greater attraction to weak associates. This tendency is visualized in Fig. 7 where we plot the likelihood of clicking an item (regardless of its status as a target or non-target) as a function of its acceptability (as rated by a separate group of participants). The function for each stimulation group was fit via a logistic regression based on the number of times a given item was chosen relative to the number of times it was shown. The anodal group had an increased likelihood of selecting items with intermediate acceptability values. Because low-dimensional categories tend to have targets with lower-acceptability values, the change in selection likelihood affects these categories disproportionately. As discussed above, we believe that the difference in acceptability (and inter-item relatedness) for the high- and low-dimensional categories reflect an inherent difference in category structure rather than a choice of targets. Categories that cohere on only one dimension, such as THINGS THAT ARE RED have far fewer members deemed universally acceptable relative to categories that cohere on multiple dimensions such as HOME APPLIANCES.

6. General discussion

The process of categorization is central to human cognition. Controlled activation—the selective activation of task relevant dimensions or features—is a key component of this process. The prefrontal cortex has been implicated in cognitive control in both non-humans (e.g., Miller, 2000) and humans (e.g., Postle, Brush, & Nick, 2004; Snyder et al., 2010; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997) leading to the prediction that stimulation of this region—particularly the left prefrontal cortex—should impact categorization performance. The present work tested this prediction using transcranial direct current stimulation (tDCS) applied over this cortical region.

Our results showed that tDCS had small, but reliable effects on categorization of familiar items, affecting both the selection of target items and the rejection of non-targets/marginal targets. Cathodal stimulation—theorized to lower cortical excitability—led to a reduction in target selection for specifically those categories having lower ratings of acceptability and inter-item reliability. Anodal stimulation—theorized to increase cortical excitability—had no reliable effect on the selection of designated targets, but appeared to lower the overall threshold for item selection, leading participants to consistently select more marginal category members, e.g., a strawberry as an example of something that is soft. This result is consistent with the possibility that anodal stimulation leads to increased sensitivity to remote associates due to greater activation of the target-properties, greater suppression of the irrelevant properties, or perhaps through an increased regulation of the prepotent response (Cerruti & Schlaug, 2009). Combined, the results support the main hypothesis that stimulation over left prefrontal cortex impacts categorization, specifically the proficiency with which subjects represent *low-dimensional* categories—those categories that we theorize require high levels of cognitive control.

As evident from the norming analyses (e.g., see Fig. 3), low-dimensional categories tend to have members judged to be less universally acceptable and the group of targets is judged to have lower inter-item relatedness compared high-dimensional categories. Given that the effects of tDCS were limited to the low-dimensional categories, one interpretation of the present results is in terms of overall difficulty, with cathodal stimulation making the already difficult trials, more difficult. The full dataset does not support this conclusion. First, it is not obvious that selecting e.g., all the 'red' items is more difficult than selecting e.g., all the non-food items found in kitchens. Although there were very reliable differences in accuracy between low- and high-dimensional categories, it is unclear that this reflects a genuine difference in overall difficulty. For example, the time per-item click RTs for correct responses were significantly shorter for low-dimensional than high-dimensional items (footnote 6). In addition, as illustrated in Fig. 5, the cathode and anode groups showed differential dependencies on target acceptability and inter-item relatedness—a pattern of results difficult to account for through differences in difficulty alone.

One way to integrate the simultaneous decrease in the hit rate of the cathode group and increase in the non-target selections of the anode group is in terms of the non-linear relationship between input (e.g., activation or acceptability of an object for a target category) and output—the probability of response selection (Kello, Sibley, & Plaut, 2005; Mirman, Yee, Blumstein, & Magnuson, 2011). On this view, category and feature knowledge is encoded in the weights or long-term knowledge system that underlies the input–output mapping and "cognitive control" refers to the shape of that non-linear response function, which can be modulated by task instructions, brain stimulation, etc. Thus, a categorization task will necessarily reflect both the process of activating relevant representations in long-term memory as well as "shaping" those representations to meet the demands of the task. We believe that it is unlikely that anodal or cathodal stimulation changed the participants' knowledge of, for example, whether leopards are orange or whether mountains are large. Rather, we believe that anodal and cathodal stimulation affected the process of re-representing candidate items as members of the cued category, that is, the effect was on the selective representation of items required by the task.

The present work has several notable limitations. First, the mechanisms responsible for the change in item selections require further explication. As mentioned above, it is possible that anodal stimulation increases activation of category-relevant features, or suppresses the activation of category-irrelevant features (thereby making marginal targets more attractive), and cathodal stimulation has the opposite effect. It is also possible that cathodal and anodal stimulation have effects on entirely distinct processes. One way to distinguish these accounts is by using artificial categories that experimentally manipulate the category structure.

A second limitation is that only a single location was stimulated. We therefore cannot make claims regarding the specificity of the results. Although current evidence indicates that effects of tDCS are location specific (e.g., Antal et al., 2003; Kincses et al., 2004), it is entirely possible that in addition to LIFG—an area that has been strongly implicated in cognitive control—stimulation over other cortical areas would also impact categorization performance. The present results do not allow us to make claims regarding how tDCS over other cortical areas may affect categorization. Follow-up studies using additional stimulation sites are clearly called for.

An additional area requiring clarification is the apparent conflict between the present results and those from a recent TMS study which found that TMS delivered to the left posterior middle temporal gyrus (pMTG), but not to LIFG adversely affected performance on a task somewhat similar to our low-dimensional categorization condition, although using words rather than images as stimuli (Whitney, Kirk, O'Sullivan, Lambon Ralph, & Jefferies, 2012).

6.1. The relationship between cognitive control, categorization, and language

The LIFG, which subsumes Broca's area, has been linked to aspects of language processing (Gernsbacher & Kaschak, 2003; Hagoort, 2005; Hinke et al., 1993; Ojemann, Ojemann, Lettich, & Berger, 1989). By manipulating cognitive control demands, Thompson-Schill and colleagues have argued that LIFG/Broca's area is subserving cognitive control functions that appear to be recruited for linguistic functions (see Novick, Trueswell, & Thompson-Schill, 2010 for review). This hypothesis is based on the observation that LIFG is activated by classic "cognitive control" paradigms (e.g., Stroop, go/no-go, and working memory tasks) and by classic language tasks (e.g., word generation, resolution of syntactic or lexical ambiguities, both of which demand highly selective activation, Kan & Thompson-Schill, 2004; Novick et al., 2010; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Although there is no research, to our knowledge, that has investigated the effect of tDCS stimulation on verbal tasks requiring high vs. low levels of cognitive control, it is of interest that existing reports of stimulating left prefrontal cortex via tDCS (e.g., Iyer et al., 2005) have used paradigms requiring high levels of control such as generating words that begin with a certain letter—a task analogous to our low-dimensional categorization condition since both require the formation of a category of items that match on a single dimension, c.f., THINGS THAT ARE ORANGE, THINGS THAT BEGIN WITH LETTER 'M' (Hirshorn & Thompson-Schill, 2006). Such results suggest that effects of tDCS on LIFG function may also affect linguistic performance, arguably via modulations of cognitive control.

The evidence above is consistent with cognitive control systems mediated by LIFG being involved in both categorization and in language. However, a parallel literature suggests language may play a causal role in categorization, possibly by mediating LIFG activity. Indeed, acquired linguistic impairments have for a long time been associated with a variety of impairments on nonverbal categorization tasks. For example, many aphasic patients are impaired at sorting objects by size or color, while ignoring shape—a task requiring the abstraction of a certain color or size category from the specific objects (Goldstein, 1948; Noppeney & Wallesch, 2000 for review). After conducting and reviewing a number of such studies, Cohen, Kelter, and colleagues (The Konstanz Group) concluded that individual with aphasia have a "defect in the analytical isolation of single features of concepts" (Cohen, Kelter, & Woll, 1980; Cohen, Woll, Walter, & Ehrenstein, 1981), yet equal to controls "when judgment can be based on global comparison" (Cohen et al., 1980).

Critically, such categorization impairments do not require damage to LIFG, suggesting that functional linguistic impairments may cause cognitive control deficits which bring about categorization impairments. On this view, certain types of categorization depend on cognitive control and cognitive control is in turn *reified* by language. This is expected if language promotes categorical representations, as argued by Lupyan and colleagues (Lupyan, 2005, 2008a, 2008b, 2012; Lupyan, Rakison, & McClelland, 2007; Lupyan & Thompson-Schill, 2012).

This possibility is supported by, for example, studies showing that interfering with language through articulatory suppression/verbal interference impacts task switching performance (Baddeley, Chincotta, & Adlam, 2001; Cragg & Nation, 2010; Emerson & Miyake, 2003; Miyake, Emerson, Padilla, & Ahn, 2004) and selectively impairs subjects' ability to isolate a specific perceptual dimension such as size or color in a categorization task (Lupyan, 2009). The performance shown by subjects during verbal interference had a similar profile to the performance of a pure anomic patient LEW on an almost identical task (Experiment 7, Davidoff & Roberson, 2004). An additional source of evidence for the idea that language reifies cognitive control comes from a study using the present task with participants with aphasia (Lupyan & Mirman, submitted for publication). These patients showed a categorization profile strikingly similar to that of the cathodally stimulated subjects in the present study, and their performance on the low-dimensional trial, but not high-dimensional trials correlated with their confrontation naming performance, regardless of lesion site.

7. Conclusion

The present results provide support to the hypothesis that stimulation over the left prefrontal cortex affects categorization of familiar items, that is, one's ability of representing individual exemplars as members of specified categories. The present work also demonstrates the feasibility of using tDCS as a tool for studying the neural processes underlying categorization and, in the near future, the relationship cognitive control and language.

As this is the first study to investigate the effects of brain stimulation in a categorization task of this sort, we view it as just the beginning. In addition to clarifying the mechanisms underlying the present set of results, further questions of immediate interest include: (1) The effects of tDCS on the representation of category-diagnostic properties vs. non-diagnostic properties, and (2) the effects of stimulation of LIFG on the process of flexibly re-representing the very same item as a member of different categories depending on current task demands.

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