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More attention when speaking: Does it help or does it hurt?

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ABSTRACT

Paying selective attention to a word in a multi-word utterance results in a decreased probability of error on that word (benefit), but an increased probability of error on the other words (cost). We ask whether excitation of the prefrontal cortex helps or hurts this cost. One hypothesis (*the resource hypothesis*) predicts a decrease in the cost due to the deployment of more attentional resources, while another (*the focus hypothesis*) predicts even greater costs due to further fine-tuning of selective attention. Our results are more consistent with the *focus hypothesis*: prefrontal stimulation caused a reliable increase in the benefit and a marginal increase in the cost of selective attention. To ensure that the effects are due to changes to the prefrontal cortex, we provide two checks: We show that the pattern of results is quite different if, instead, the primary motor cortex is stimulated. We also show that the stimulation-related benefits in the verbal task correlate with the stimulation-related benefits in an N-back task, which is known to tap into a prefrontal function. Our results shed light on how selective attention affects language production, and more generally, on how selective attention affects production of a sequence over time.

1. Introduction

Selective attention can be a double-edged sword: focusing attention on one item implies not paying as much attention to other items. While selective attention has been studied extensively in visual perception (e.g. Clery, Andersson, Fonlupt, & Gomot, 2013; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Desimone & Duncan, 1995; Fries, Reynolds, Rorie, & Desimone, 2001, Lavie, 1995; Maris, Womelsdorf, Desimone, & Fries, 2013; Moran & Desimone, 1985; Treisman, 1969), little attention has been paid to selective attention in language production. Studies of visual attention suggest that objects in the visual input compete for processing in a system with limited capacity, such that an increase in the number of the to-be-attended items, usually makes the task more difficult (e.g. Desimone & Duncan, 1995). However, competition in the system can be quite selective and biased towards processing of the stimulus that is currently relevant to behavior. The evidence for the biased competition comes from studies showing that, unlike the number of relevant stimuli, the number of irrelevant stimuli (distractors) may have no influence on performance (Bundesen, 1990; Duncan, 1980).

These findings have led to the proposal of models in which attention is viewed as an emergent property of the neural systems that must resolve competition to generate the desired output (Desimone & Duncan, 1995; Miller, 2000). Detailed computational models of various levels of complexity have implemented biased competition for spatial and object-oriented attention (Deco & Lee, 2002; Lanyon & Denham, 2004; Usher & Niebur, 1996). A similar mechanism of biasing competition has been implemented to explain goal-oriented action (Cisek, 2006). More recently, the biased activation model has been used to explain top-down attentional modulation of affect (e.g. Grabenhorst & Rolls, 2010; Rolls, 2013). While this mechanism is plausible for any system, there are clear differences between the visual system, which is predominantly perception-based, and the language production system, which is much less affected by the numerous bottom-up factors known to influence competition during visual object selection (see Desimone & Duncan, 1995 for a complete review of these factors). These differences motivate research on selective attention in the context of language production. More generally, the sequential nature of language production allows for studying the effects of selective attention in *time*, as opposed to *space* (which is the usual focus of studies of visual attention). This difference is an asset, as it makes research on selective attention in language production not only useful for understanding the interaction between the language production and executive systems, but also informative about the nature of competition-biasing mechanisms in space vs. time.

There is reason to believe that there are some parallels between selective attention in visual perception and in language production. For example, capacity limitation has also been demonstrated in production tasks requiring selective processing of one word in a sequence of words. Nozari and Dell (2012) used a verbal selective attention paradigm, in which participants had to recite 4-word

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tongue-twisters. Although these tongue-twisters are not coherent sentences, there is evidence that they are indeed treated as real words and not just sequences of phonemes (Oppenheim & Dell, 2008). One or none of the words was highlighted on each trial. Participants were told to avoid making errors, particularly on a highlighted word. In this, and two other experiments where participants had to either verbally emphasize, or alternatively to silently mouth the highlighted word, Nozari and Dell showed that selectively attending to one word in a sequence increased accuracy on that word, but decreased accuracy on other words in the sequence. These results suggest that while there is a benefit to focusing attention, there is a cost as well.

It is well-established that spatial attention operates through an extensive network, involving two prominent cortical areas, the prefrontal cortex (PFC) and the parietal cortex (e.g. Corbetta, 1998; Frank & Sabatinelli, 2012; Hales & Brewer, 2013; Ptak, 2012). Of the two, the role of the PFC has been extended from attention to location to other domains, such as attention to object identity (Wilson, Scalaidhe, & Goldman-Rakic, 1993), although different parts of the PFC may be responsible for the two functions, reflecting extensions of dorsal and ventral streams (Mishkin, Ungerleider, & Macko, 1983). Similarly, a functional distinction had been made between the parietal cortex and the PFC, by suggesting that the former is involved in activating multiple responses, while the latter is responsible for selection among the competing responses (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002). Moreover, frontal operculum is selectively activated when attentional resources are limited by temporal – as opposed to spatial – factors (Coull, 2004).

The role of PFC in biasing competition is also well-established in both comprehension and production of language. For example, in verb generation tasks, left PFC shows greater activation for generating verbs in response to nous that are associated with many possible verbs (e.g., "cat"→eat, meow, play, purr, etc.), as opposed to nouns that clearly elicit one verb (e.g., "scissors"→cut; Thompson-Schill, D′Esposito, Aguirre, & Farah, 1997). Similarly in comprehension, when subjects are asked to judge the similarity between items, left PFC shows greater activation for judgments based on a single dimension, while ignoring other dimensions (e.g., judging whether "tooth" is more similar to "bone" or "tongue" in color), compared to global similarity judgments without selecting a single dimension (Thompson-Schill et al., 1997). Within the global judgment task too, left PFC shows stronger activation in response to items with weak associations (e.g., "candle" and "halo") compared to items with high association (e.g., "candle" and "flame"; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001). Patient and TMS studies corroborate these findings and establish a causal role for the left PFC in biasing competition (e.g., Thompson-Schill et al., 1998; Whitney, Kirk, O′Sullivan, Ralph, & Jefferies, 2011). Other examples of left PFC involvement in biasing competition in linguistic contexts includes processing of sentences with syntactic ambiguity (January, Trueswell, & Thompson-Schill, 2009; Keller, Carpenter, & Just, 2001; Mason, Just, Keller, & Carpenter, 2003; Novick, Kan, Trueswell, & Thompson-Schill, 2009), where top-down biasing is required for suppressing one meaning in favor of another. Recently, Rodd, Johnsrude, and Davis (2012) showed that left PFC responds to both the ambiguous word in the sentences and to the disambiguating information, clearly indicating that the role of this region is not limited to "revision" alone, but is related to operations involved in biasing towards the relevant meaning whenever the cognitive system is faced with competing alternatives.

In recent years it has been suggested that trouble with biasing competition can give rise to a clinical syndrome called dynamic aphasia (Robinson, Shallice, Bozzali, & Cipolotti, 2010; Robinson, Shallice, & Cipolotti, 2005) in which patients' propositional speech is severely reduced, in spite of having good picture naming (at least when the name agreement is high), word repetition or comprehension skills. Robinson et al. (2010) have shown that these patients, who suffer from damage to the left inferior PFC, have a selective deficit in generating sentences in response to unconstrained prompts. For example, such patients have a much more difficult time generating a sentence from high frequency nouns, compared to low frequency and proper nouns which are much more constraining in their meaning. While consequences of a disruption in the process of biasing competition have been well documented, it remains to be seen what the consequences are for augmenting this process. This paper addresses this issue.

In this paper, we investigate the change to the cost–benefit pattern of selective attention as a function of exciting the PFC. To this end, we applied anodal transcranial direct current stimulation (tDCS) to the left PFC, and examined post-tDCS pattern of cost–benefit as subjects recited the four-word tongue-twisters. The goal of the paper is, in part, to understand the nature of selective attention in language production and, in part, to understand, more generally, the consequences of exciting the neural tissue that implements competition resolution. Note that the production sequence unfolds over time. At each time point competition must be resolved in favor of a different word. In a hypothetical cognitive system with no resource limitation, competition resolution would be perfect for each item, and the top-down bias in favor of item x at time t would not influence the bias to choose item y at time $t+1$. This is, however, not true for our resource-limited cognitive systems. Once attentional resources are allocated to processing of an item, either in space or in time, processing of other items will suffer. Is this because only a fraction of neuronal resources are recruited, or is this an inherent feature of the way competition resolution is implemented in the PFC? We seek answers to these questions under two opposing hypotheses: (1) *The resource hypothesis*: if the cost is due the insufficient recruitment of the PFC neurons, then stimulation should decrease the cost associated with selective attention. (2) The *focus hypothesis:* if the cost is a direct consequence of the successful biasing, then PFC stimulation could be expected to exaggerate the cost. Under both predictions, however, greater benefits (i.e. fewer errors on the attended word) would be expected.

Because employing tDCS for studying an executive process in the context of language production is new, we have implemented two controls in the design, to ensure that our results are truly due to changes in the PFC, and not task-specific processes. The first control tests whether performance in the tongue-twister task is similarly affected by the stimulation of a different brain region (primary motor cortex, or M1). This control site was chosen based on its involvement in processing phonological/phonemic elements (e.g., Schwartz, Faseyitan, Kim, & Coslett, 2012), without involvement in attentional processes. If the changes to the cost–benefit pattern under PFC stimulation are specific to the PFC, we expect a difference between the PFC- and M1-induced stimulation patterns. The second control aims to replicate a previous finding regarding the effect of anodal stimulation of the PFC. The N-back task is known to benefit from PFC stimulation (Fregni et al., 2005; Marshall, Molle, Siebner, & Born, 2005; Ohn et al., 2008; Zaehle, Sandmann, Thorne, Jaencke, & Herrmann, 2011). We have, therefore, had our participants complete an N-back task in the same session as they completed the tongue-twister task. Our purpose was two-fold: by replicating the finding that the N-back task benefits from PFC stimulation, we would (1) validate our stimulation protocol, and (2) create a potential index of improvement in working memory, which we could then correlate with improvement in our selective attention task. The implications of this correlation will be discussed in detail in Section 4.

1.1. PFC stimulation

tDCS is a simple and safe (Iyer et al., 2005) method for altering behavior by inducing changes in the resting membrane potential