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Research report

tDCS to temporoparietal cortex during familiarisation enhances the subsequent phonological coherence of nonwords in immediate serial recall

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ABSTRACT

Research has shown that direct current stimulation (tDCS) over left temporoparietal cortex – a region implicated in phonological processing – aids new word learning. The locus of this effect remains unclear since (i) experiments have not empirically separated the acquisition of phonological forms from lexical-semantic links and (ii) outcome measures have focused on learnt associations with a referent rather than phonological stability. We tested the hypothesis that left temporoparietal tDCS would strengthen the acquisition of phonological forms, even in the absence of the opportunity to acquire lexical-semantic associations. Participants were familiarised with nonwords paired with (i) photographs of concrete referents or (ii) blurred images where no clear features were visible. Nonword familiarisation proceeded under conditions of anodal tDCS and sham stimulation in different sessions. We examined the impact of these manipulations on the stability of the phonological trace in an immediate serial recall (ISR) task the following day, ensuring that any effects were due to the influence of tDCS on long-term learning and not a direct consequence of short-term changes in neural excitability. We found that only a few exposures to the phonological forms of nonwords were sufficient to enhance nonword ISR overall compared to entirely novel items. Anodal tDCS during familiarisation further enhanced the acquisition of phonological forms, producing a specific reduction in the frequency of phoneme migrations when sequences of nonwords were maintained in verbal short-term memory. More of the phonemes that were recalled were bound together as a whole correct nonword following tDCS. These data show that tDCS to left temporoparietal cortex can facilitate word learning by strengthening the acquisition of long-term phonological forms, irrespective of the availability of a concrete referent, and that the consequences of this learning can be seen beyond the learning task as strengthened phonological coherence in verbal short-term memory.

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1. Introduction

A wealth of neuroimaging studies show that structures within left temporoparietal cortex (TPC), including supramarginal gyrus, posterior superior temporal gyrus and sulcus, and temporoparietal junction within the sylvian fissure, contribute to phonological processing and verbal short-term memory (STM). In posterior perisylvian cortex, activation during phonological encoding is positively associated with subsequent memory for nonwords (Clark & Wagner, 2003; see also Breitenstein et al., 2005; Paulesu et al., 2009) and for foreign words (Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010). Left temporoparietal activity during the repetition of nonwords correlates with phonological-lexical learning and is associated with the retrieval of whole word phonology (Graves, Grabowski, Mehta, & Gupta, 2008; Majerus et al., 2005). Moreover, the left supramarginal gyrus has been specifically linked with the perception (e.g., Jacquemot, Pallier, LeBihan, Dehaene, & Dupoux, 2003; Liebenthal, Sabri, Beardsley, Mangalathu-Arumana, & Desai, 2013; Raizada & Poldrack, 2007; Turkeltaub & Coslett, 2010) and sequencing of phoneme segments (Gelfand & Bookheimer, 2003; Moser, Baker, Sanchez, Rorden, & Fridriksson, 2009).

This literature is consistent with recent findings showing that electrical stimulation to left TPC augments the learning of nonword phonological forms. Transcranial direct current stimulation (tDCS) involves passing a small current through the brain via electrodes on the scalp. Cortical excitability is increased (and the capacity for learning enhanced) by positioning the anode over a functionally-relevant site, and the cathode (or reference electrode) over a distinct scalp or extracephalic site (see Nitsche et al., 2008). Anodal stimulation to left TPC has been shown to boost the acquisition of new vocabulary, using both auditory and written stimuli (Flöel, Rösser, Michka, Knecht, & Breitenstein, 2008; Meinzer et al., 2014). Flöel et al. (2008) found that tDCS to TPC facilitated the learning of pairings between spoken monosyllabic nonwords and pictures of familiar objects using a statistical learning paradigm. Fiori et al. (2011) reported that tDCS to this location aided the retrieval of newly-acquired picture names in healthy subjects and had a similar effect on picture naming in participants with aphasia. Meinzer et al. (2014) extended this work in healthy subjects by applying tDCS on five consecutive days: anodal tDCS increased the cumulative learning seen for written nonwords paired with both familiar (nameable) objects and unfamiliar entities, and these gains were still present at a follow-up one week after the last stimulation session. These findings indicate that repeated applications of tDCS can have long-term benefits on word learning. In contrast, the long-term effects of a *single* application of tDCS have not been established because these previous studies assessed the effects of tDCS immediately after stimulation, when potential effects on long-term learning are confounded by short-term increases in cortical excitability.

In addition, while these studies show that tDCS can facilitate word learning, the mechanisms underpinning these effects are not clear. In particular, further research is needed to establish whether tDCS over left temporoparietal cortex produces improvement in word learning by facilitating (i) the acquisition and retrieval of associations between new words and objects (i.e., lexical-semantic learning) or (ii) the learning of novel phonological forms themselves even in the absence of an association with a meaningful object (i.e., acquisition of phonological-lexical representations). Studies to date have exclusively examined new word learning when a concrete referent is present. However, if left temporoparietal cortex is critical for encoding phonemic sequences into new phonological-lexical representations (as indicated by, for example, Baddeley, 2003; Graves et al., 2008; Gupta & MacWhinney, 1997; Paulesu et al., 2009; Sato et al., 2004), we would anticipate that tDCS to left temporoparietal cortex would have a similar effect on nonword learning with and without the availability of a concrete referent, at least when using tasks that tap the stability of phonological processing per se as opposed to vocabulary knowledge.

To test this possibility, we made use of research showing strong effects of phonological-lexical learning on the stability of the phonological trace in immediate serial recall (ISR) tasks. In ISR, participants hear a sequence of words or nonwords and have to repeat the sequence back immediately in the correct order. The frequency with which phonemes from one item break apart and recombine with the elements of other items depends on the availability of long-term phonological-lexical representations (Hoffman, Jefferies, Ehsan, Jones, & Lambon Ralph, 2009; Jefferies, Frankish, & Lambon Ralph, 2006a, 2006b; Jefferies, Frankish, & Noble, 2009). For example, in healthy participants, we know that when the phonological system attempts to maintain several unfamiliar nonwords in order, phonological segments frequently migrate and recombine with the elements of other items or are lost altogether (for example, 'gid heem jurn' might be recalled as 'jid heen churm'). In contrast, when target items are familiar words, the frequency of these errors is greatly reduced and instead entire items are recalled out of sequence (for example, 'sash, king, cot, wall, heap' might be recalled as 'sash, cot, wall, king, heap') (Ellis, 1980; Jefferies et al., 2006a, 2009; Treiman & Danis, 1988). Such lexicality effects in ISR are preserved when words and nonwords are mixed predictably (or unpredictably) in the same list (Hoffman et al., 2009; Jefferies et al., 2006a, 2009), showing that they cannot solely reflect a strategic editing process during speech production, in which nonword responses in word lists are replaced with real words based on knowledge of the lexical status of the targets (although such effects are also observable; Jefferies et al., 2009). Instead, it appears that there is a direct impact of lexical knowledge on phonological stability. ISR data such as these provide a strong case for verbal short-term memory drawing on long-term linguistic representations (Acheson, Hamidi, Binder, & Postle, 2011; Jefferies et al., 2006a; Patterson, Graham, & Hodges, 1994), in line with a wealth of studies which show effects of lexicality (i.e., words *vs* nonwords: Hulme, Maughan, & Brown Gordon, 1991; Hulme, Roodenrys, & Brown, 1995; Majerus & Linden, 2003; Saint-Aubin & Poirier, 1999, 2000) and phonotactic frequency (i.e., differences in phonotactic frequence between nonwords: Majerus & Linden, 2003; Nimmo & Roodenrys, 2002; Thorn & Frankish, 2005) on ISR accuracy at the whole-item level. We hypothesise that lexical learning involves acquiring a phoneme sequence, allowing the identity of upcoming phonological elements to be predicted,