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Language Learning without Control: The Role of the PFC

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Abstract

■ Learning takes place throughout lifetime but differs in infants and adults because of the development of the PFC, a brain region responsible for cognitive control. To test this hypothesis, adults were investigated in a language learning paradigm under inhibitory, cathodal transcranial direct current stimulation over PFC. The experiment included a learning session interspersed with test phases and a test-only session. The stimulus material required the learning of grammatical dependencies between two elements in a novel language. In a parallel design, cathodal transcranial direct current stimulation over the left PFC, right PFC, or sham stimulation was applied during the learning session but not during the test-only session. Event-related brain potentials (ERPs) were recorded during both sessions. Whereas no ERP learning effects were observed during the learning session, different ERP learning effects as a function of prior stimulation type were found during the test-only session, although behavioral learning success was equal across conditions. With sham stimulation, the ERP learning effect was reflected in a centro-parietal N400-like negativity indicating lexical processes. Inhibitory stimulation over the left PFC, but not over the right PFC, led to a late positivity similar to that previously observed in prelinguistic infants indicating associative learning. The present data demonstrate that adults can learn with and without cognitive control using different learning mechanisms. In the presence of cognitive control, adult language learning is lexically guided, whereas it appears to be associative in nature when PFC control is downregulated. ■

INTRODUCTION

Learning is a crucial aspect of human development throughout life, but it appears to change as the brain matures (Ramscar & Gitcho, 2007). It has been argued that the delayed maturation of the PFC compared with other cortical regions (Chugani & Phelps, 1986) is a major parameter in determining infant compared with adult learning (Thompson-Schill, Ramscar, & Chrysikou, 2009). In adults, it has been shown that the left PFC plays a role in memorization of verbal material (Elmer, Burkard, Renz, Meyer, & Jancke, 2009); however, if and which role it plays during the extraction of linguistic rules from verbal input is yet unknown. The goal of this study was to test the role of PFC in adult learning by downregulating the function of PFC using noninvasive transcranial direct current stimulation (tDCS).

In the adult brain, PFC supports cognitive control (Thompson-Schill et al., 2009; Badre, 2008; Koechlin & Summerfield, 2007), and it has been convincingly shown that, in the adult brain, PFC control processes modulate processes located in the temporal, parietal, and occipital regions in a top–down manner (for reviews, see Gazzaley & D'Esposito, 2007; Corbetta & Shulman, 2002). For infants, it is hypothesized that such control processes are not yet functionable because of a delayed maturation of PFC and that, therefore, associative processes located in temporal cortices may work uninfluenced by cognitive control in a more effective manner than in adults (Thompson-Schill et al., 2009). This should hold, in particular, for learning early in life.

Thus, associative learning, which relates temporally contiguous elements when one element is predictive of another, should be very efficient in early infancy. This has been shown particularly well for language learning. In their first months of life, infants are already able to learn the stress pattern of their native language (Weber, Hahne, Friedrich, & Friederici, 2004) and use predictive probabilities between syllables to segment word-like units (Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009; Saffran, Aslin, & Newport, 1996). Recently, it has been shown that even more complex regularities in language, which relate two nonadjacent linguistic elements with each other in an auditory sequence, can be already acquired by 4-month-olds after brief exposure (Friederici, Mueller, & Oberecker, 2011). This learning effect was evidenced by a clear difference in the event-related brain potentials (ERPs) for correct and incorrect sentences in the test phases of the study. It was assumed that these prelinguistic infants had learned the grammatical dependency between the two crucial elements in the sentence on the basis of a phonology-based associative process, that is, a process that does not require cognitive control. When the same implicit learning paradigm was applied to German-speaking adults, no learning effect was found neither in the ERPs nor in the behavioral data (unpublished

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data, Jutta Mueller). However, when the paradigm was combined with a grammaticality judgment task, adult learners' ERP showed a learning effect that differed from the one observed in infants. Whereas infants displayed a centro-parietal positivity, adults showed a centro-parietal N400-like negativity and an anterior positivity (Citron, Oberecker, Friederici, & Mueller, 2011; Mueller, Oberecker, & Friederici, 2009). The observed N400-like negativity was taken to reflect lexical processes usually indicated by an N400 (Lau, Philipps, & Poeppel, 2008; Chwilla, Brown, & Hagoort, 1995), and the early anterior positivity was taken to reflect attention-related processes (Mueller et al., 2009; Friedman, Cycowicz, & Gaeta, 2001).

Thus, these studies suggests that infant learning differs from adult learning in several aspects. First, infants implicitly learn grammatical dependencies implicitly by mere exposure (Friederici et al., 2011), whereas grammatical learning in adults has only been documented in tasks that require a grammaticality judgment (Mueller et al., 2009). Note, however, that implicit learning in adults has been shown for word segmentation based on adjacent dependencies between syllables (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997), for word form to meaning mapping (Breitenstein & Knecht, 2002), and for artificial grammars defined by local transitional probabilities (Saffran, 2001). To our knowledge, implicit learning of nonadjacent dependencies in adults has yet to be demonstrated. Typical studies in this field (e.g., Gòmez, 2002) use an "active listening" instruction, and a recent study reported adults' failure to learn a nonadjacent dependency in the absence of an active learning task whereas infants were partly successful (Mueller, Friederici, & Männel, 2012). Second, the infants' ERP learning effect was shown to be reflected by a centro-parietal positivity (Friederici et al., 2011), whereas the adult learning effect was expressed as a centro-parietal N400-like negativity and an anterior positivity reflecting controlled lexically based learning processes (Mueller et al., 2009).

This interpretation is generally in line with the hypothesis that adult learning is more controlled, whereas infant learning is associative without control (Thompson-Schill et al., 2009). If the observed results for language learning are a reflection of this general developmental change in learning because of the maturation of PFC (Ramscar & Gitcho, 2007), adult language learning should be altered if the activity of PFC is downregulated, thereby decreasing the influence of controlled processes.

One method to transiently alter cortical activity noninvasively is tDCS. tDCS has different effects on the brain's excitability depending on the polarity of the stimulation electrode (Nitsche & Paulus, 2000). Anodal tDCS increases the excitability in the cortex underlying the stimulating electrode and leads to improved learning. This has been demonstrated in the motor (Nitsche et al., 2003) and visuo-motor domain (Antal et al., 2004) as well as in lexical learning (Flöel, Roesser, Miichka, Knecht, & Breitenstein, 2008). Cathodal tDCS, in contrast, leads to a decrease in cortical excitability (Nitsche et al., 2003). The underlying neurophysiological processes associated with anodal stimulation are thought to be based on changes comparable to long-term potentiation, whereas those associated with cathodal stimulation seem to be related to long-term depression-like changes (Rioult-Pedotti, Friedman, & Donoghue, 2000).

Here, we applied cathodal tDCS over the left and right PFC with the goal of downregulating this region's excitability and, thereby, its effectiveness in cognitive control. Under the hypothesis that PFC supports processes of cognitive control in the mature brain (Thompson-Schill et al., 2009; Koechlin & Summerfield, 2007), we reasoned that cognitive control functions should be decreased under cathodal tDCS. We hypothesized that stimulation over left PFC and right PFC would lead to differential effects because these regions support different cognitive processes. The left PFC is known to be involved in phonological, syntactic, and semantic processes (Hagoort, 2005; Friederici, 2002) and to support syntactic learning (Flöel et al., 2008; Udden et al., 2008). We, therefore, hypothesized that downregulation of the left PFC should directly influence the specific mechanisms of language learning (Thompson-Schill, Bedny, & Goldberg, 2005; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). The right PFC has been discussed as a region involved in directing attention to relevant sensory stimuli (Corbetta & Shulman, 2002). We, therefore, hypothesized that the downregulation of the right PFC should modulate general attention-related aspects of learning. Applying ERP as the dependent variable, we were able to show that under the downregulation of the left and right PFC lead to different learning mechanisms.

METHODS

Participants

Forty-nine native speakers of German (age range = 21–29 years, mean = 24.3 years, *SD* = 2.1, 23 women) with no knowledge of Italian participated in this study. All participants were right-handed and had no hearing or neurological disorder. All participants gave written informed consent in accordance with the declaration of Helsinki before the experiment. The study was approved by the local ethics committee of the University of Leipzig.

Stimuli

The Italian sentences used in the study were identical to those used in an earlier study with infants (Friederici et al., 2011). These sentences contained two animate noun phrases, namely *il fratello*/brother or *la sorella*/sister, two different auxiliaries (*può*/to be able to or *sta*/to be), and 32 verbs occurring either in the infinitive (e.g., *cantare*/to sing) or in the progressive form (e.g., *cantando*/singing). Mean length of the verb stems was 260 msec (verb stem plus *-are*: 452 msec, verb stem plus *-ando*: 530 msec; for acoustic analyses of the stimulus material, see Friederici et al., 2011). Within the sentences, a rule-based dependency existed between two nonadjacent elements: the auxiliary and the main verb's suffix; the auxiliary *può* required the infinitive verb form (i.e., X-*are*; e.g., *la sorella può cantare*), whereas the auxiliary *sta* required the progressive form (i.e., X-*ando*; e.g., *la sorella sta cantando*). In total, 128 different correct sentences with 32 different verbs were created. Incorrect sentences included a wrong combination between the auxiliary and the following verb form (i.e., *può* X-*ando*, *sta* X-*are*). Both the correct and incorrect sentences were generated in the same manner using a cross-splicing procedure, exchanging the verb with the verb from a different sentence. Cross-splicing was used in both conditions to avoid any possible acoustic difference between correct and incorrect sentences. All sentences were spoken with a sentence intonation by a female native speaker of Italian and digitally recorded. A total of 96 correct sentences were created. For each participant, 64 of these 96 correct sentences were chosen for the learning phases, and 32, for the test phases. During each learning phase, all 64 correct sentences were presented in pseudorandomized order. The remaining 32 of the 96 correct sentences and 32 corresponding grammatically incorrect sentences occurred during the test phases. Each of the four test phases consisted of eight correct and eight incorrect sentences.

Procedure

The experiment consisted of two sessions during which sentences were presented auditorily: a combined learning-plus-test session with stimulation and a subsequent test-only session without stimulation.

The learning-plus-test session contained four alternate learning and test phases, starting with a learning phase and ending with a test phase. Each learning phase lasted approximately 3.3 min; each test phase lasted about 1.3 min. In the learning phases, the ISI was 3000 msec, whereas it was 5000 msec in the test phases. The learning-plus-test session lasted about 18.5 min. In the learning-plus-test session, participants were required to attentively listen to the stimulus material and no further task was given. During the learning-plus-test session, participants received cathodal tDCS over the left PFC, the right PFC, or sham stimulation.

In the test-only session, a behavioral response (grammaticality judgment) was required. In this session, no stimulation was applied. During the test phases, the trials started with a fixation cross appearing in the middle of the screen for 1000 msec. Then, the test sentence was presented, and 3000 msec after the end of the sentence, a happy and a sad face appeared on the screen and participants had 2000 msec in which to give a grammaticality judgment. To do this, participants used a three-button response box (the middle button of which was not used) with the left button corresponding to the "correct" judgment for 50% of the participants and the right button for the other 50%.

EEG was recorded during both sessions. To minimize eye movements, participants saw a fixation cross in the middle of a screen placed in front of them.

tDCS

tDCS was delivered by a constant DC stimulator (Eldith DC-Stimulator, NeuroConn GmbH, Ilmenau, Germany) using pairs of saline-soaked (5 × 5 cm) sponge electrodes. The cathodal electrode was centered over the respective target area, left or right PFC (left PFC: F3, right PFC: F4), based on the international 10–20 system of electrode placement. The anode was attached to the contralateral supraorbital region (see Figure 1). For all conditions (anodal tDCS over left PFC, right PFC, and sham), the current was increased in a ramp-like fashion over 30 sec to a maximum of 1 mA eliciting a transient tingling sensation on the scalp. Although tDCS was delivered for 20 min in the verum tDCS groups, the stimulation was faded out after only 30 sec in the sham group. The current density at the stimulation electrodes amounted to 0.04 mA/cm^2, and total charge (Current density × Total stimulation duration in sec) was 0.048 C/cm^2 for the verum conditions. At the end of stimulation, currents were turned off slowly over a few seconds to preclude sensory differences between conditions.

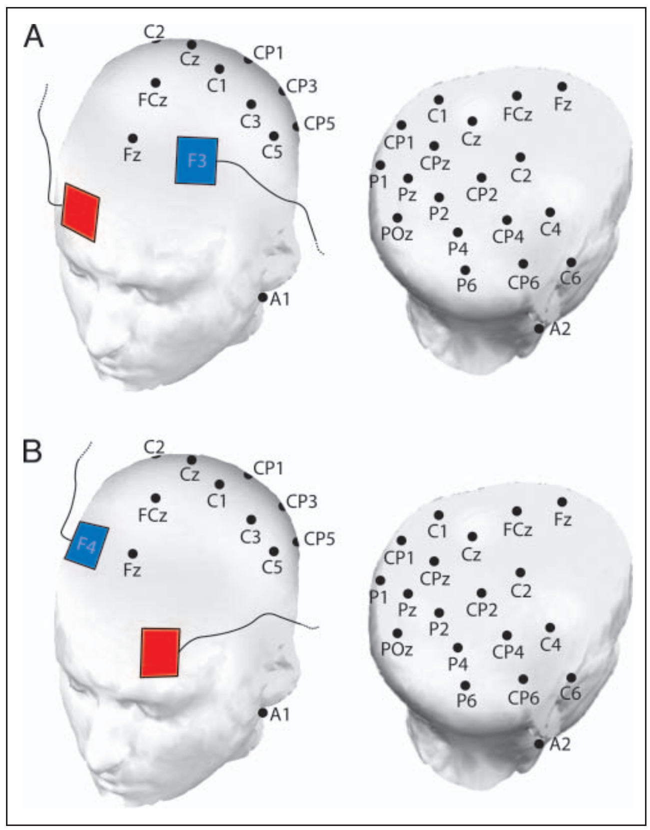

Figure 1. Schematic view of the positioning of the EEG electrodes (black dots) and the cathodal stimulation electrode (red square) and reference electrode (blue square). (A) Cathodal stimulation over the left PFC. (B) Cathodal stimulation over the right PFC.

Stimulation over the left PFC, the right PFC, or sham stimulation was applied throughout the learning-plus-test session.

Data Recording and Analysis

The EEG was continuously recorded from Ag–AgCl electrodes at sites Fz, FCz, C5, C6, C3, C4, C1, C2, Cz, CP5, CP6, CP3, CP4, CP1, CP2, CPz, P5, P6, P3, P4, P1, P2, Pz, POz, A1, and A2 (according to the extended 10–20 international system of electrode placement). The electrodes were secured in an elastic electrode cap (Easy Cap, Brain Products, Gilching, Germany), and the ERP electrodes were referenced to A1 during recording. EOGs were recorded monopolar infraorbital to the right eye (V+) as well as from an electrode located lateral to the right eye (H+). The electrode impedances were mostly kept below 10 kV and always below a maximum of 15 kV. The electrical signals were digitized with a sampling rate of 500 Hz. The EEG was algebraically rereferenced to the average of both mastoids (A1, A2). A zero-phase digital band-pass filter ranging from 0.3 to 20 Hz (23-dB cutoff frequencies of 0.38 and 19.91 Hz) was used to remove drifts and muscle artifacts from the EEG while still preserving most of the original signal. Ocular artifacts were removed by using independent component analysis as implemented in EEGLAB 6.0 (Delorme & Makeig, 2004). In the following step, trials including amplitude changes over 100 μV within the epoch were rejected automatically. ERPs were analyzed for each participant during the test phase for correct and incorrect sentences conditions for 1200 msec time-locked to the onset of the critical verb with a 200-msec prestimulus baseline. To investigate the grammaticality effect for all test phases, an ANOVA with the factors stimulation (left PFC, right PFC, sham stimulation), condition (correct/incorrect), and ROI (left lateral: C5, CP3, P3; left medial: C1, CP1, P1; fronto-central: Fz, FCz, C; posterior central: CPz, Pz, Poz; right medial: C2, CP2, P2; right lateral: C4, CP4, P4) was conducted. On the basis of visual inspection of the results (cf. Hanulikova, van Alphen, van Goch, & Weber, 2012; Pakulak & Neville, 2011, for similar procedure), we chose the following time windows (TWs), time-locked to the verb onset, for analysis: 280–380 msec (TW 1: anterior positivity, P2) 350–500 msec (TW 2: N400-like negativity), and 650–900 msec (TW 3: late positivity). For all ANOVAs, the Greenhouse–Geisser correction was applied whenever there was more than 1 *df*.

RESULTS

The experiment involved a passive learning session (with short interspersed test phases) during which tDCS was applied and a test-only session during which grammaticality judgment was required (see Figure 2).

ERPs recorded during the learning session in which passive listening was required revealed no ERP learning effect for the test phases in any of the three experimental conditions.

For the test-only session in which a grammaticality judgment was required, a behavioral learning effect with 65–70% (mean = 68.0%, SD = 25.3%) correct performance with no significant difference between the conditions was found. However, ERPs revealed significantly different patterns as time-locked to the suffix of the critical verb (see Figure 3). In the 280–380 msec TW (TW 1), the ANOVA with the factors Stimulation (left PFC, right PFC, sham stimulation), Condition (correct vs. incorrect), and ROI (left lateral, left medial, fronto-central, posterior central, right medial, right lateral) revealed a significant Condition × Stimulation × ROI interaction ($F(10, 230) = 2.28$, $p < .05$). In the 350–500 msec TW (TW 2), there was a marginal, although not fully significant, interaction of Condition × Stimulation × ROI ($F(10, 230) = 2.03$, $p = .083$). In the 650–900 msec TW (TW 3), there was a significant interaction of Stimulation × Condition ($F(2, 46) = 4.15$, $p < .05$). Step-down analyses in TW 1 showed a significant ROI × Condition interaction for sham stimulation ($F(5, 80) = 6.37$, $p < .001$) but not for the two other stimulation types. The sham stimulation revealed an early positivity, significant over fronto-central electrodes ($F(1, 16) = 6.02$, $p < .05$). For TW 2, a significant ROI × Condition interaction was found for sham stimulation ($F(5, 80) = 3.43$, $p < .05$) resulting from a negativity over posterior central electrode sites ($F(1, 16) = 4.66$, $p < .05$). Analysis of TW 3 revealed a significant main effect of condition for left stimulation ($F(1, 16) = 6.23$, $p < .05$) resulting from a positivity for incorrect items.

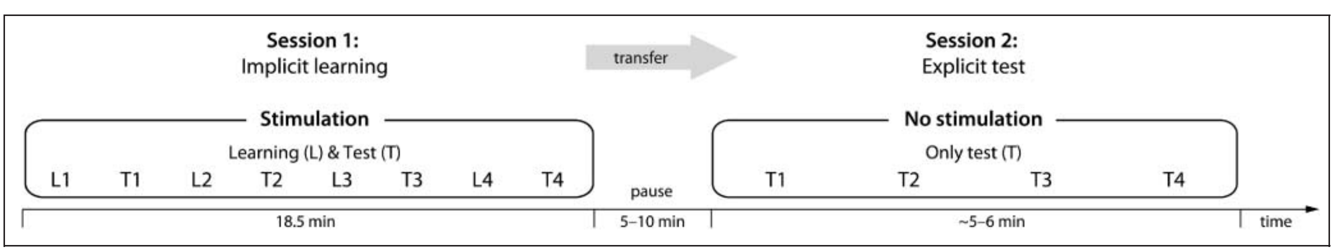

Figure 2. Experimental procedure. The experimental procedure consisted of two sessions. Session 1 contained four learning phases of approximately 3.3 min (64 correct sentences) and four short test phases of approximately 1.3 min (eight correct and eight incorrect sentences) during which stimulation (left PFC, right PFC, and sham) was applied. Session 2 contained four test sessions of 1.3 min during which no stimulation was applied.

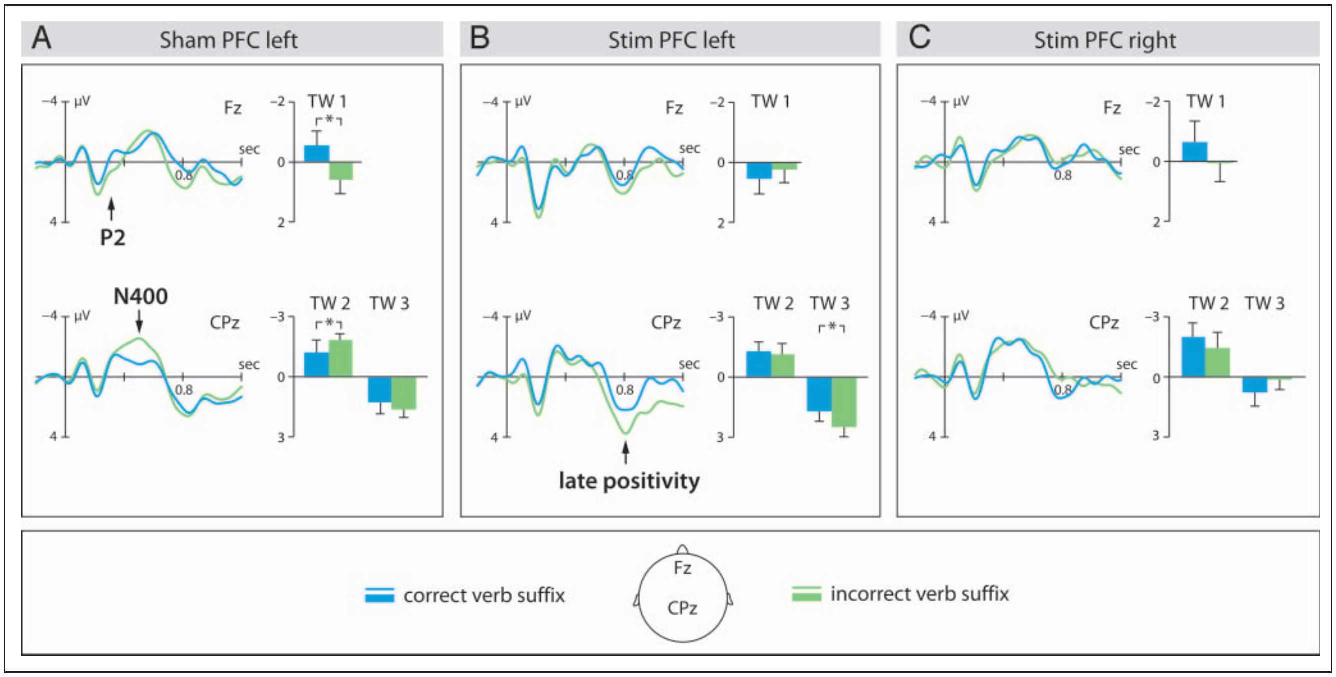

Figure 3. ERP results. Grand-averaged ERPs for the three types of stimulation: sham (A), left PFC (B), and right PFC (C) for the frontal electrode Fz and the centro-parietal electrode CPz. ERPs (left) and mean amplitudes (right) for different TW bars are displayed for correct (blue) and incorrect (green) sentences for each stimulation type. In the ERP plots, the vertical line marks the onset of the verb suffix and negativity is plotted upwards. In the amplitude plots, display bars for the different TWs: TW 1, 280–380 msec (P2); TW 2, 350–500 msec (N400); and TW 3, 650–900 msec (late positivity). Significant effects are indicated by *, that is, $p < .005$.

For the right PFC stimulation, we observed a trend towards a condition effect in the form of a negative deflection in the ERPs, which, however, did not reach significance ($F(1, 14) = 3.14$, $p = .098$). For sham stimulation, no effect was found.

DISCUSSION

This study tested the hypothesis that downregulation of the activity in the left PFC by means of cathodal tDCS leads to reduced cognitive control during adult learning and, thereby, to altered learning mechanisms. The present data provide evidence for this hypothesis by showing that cathodal tDCS over the left PFC, right PFC, and sham leads to different ERP learning effects. In particular, stimulation over the left PFC revealed an ERP pattern for rule learning in language in adults, which resembles that observed for infants, where associative learning is assumed to occur because of an immaturity of the PFC (Ramscar & Gitcho, 2007).

Here, a passive listening paradigm similar to that of prior infant and adult studies was used. This paradigm tested for the learning of a rule-based dependency, which represents a grammatical rule in Italian, that is, the dependency between particular auxiliaries and the main verb's suffix, by mere exposure. Previous research had shown that this dependency in Italian can be learned by 4-month-old native German infants after brief exposure to correct Italian sentences, as revealed by a significant difference in the ERPs to incorrect and correct sentences during a test in a passive listening learning-plus-test paradigm (Friederici et al., 2011). In infants, this difference was expressed as a positivity in response to the incorrect condition between 640 and 1040 msec after the onset of the critical verb's suffix. Interestingly, a similar positivity could not be found in adults neither during passive listening nor when applying an active version of the paradigm requiring an explicit grammaticality judgment during test (Mueller et al., 2009). Instead, the grammaticality judgment paradigm led to an ERP learning effect in the form of a centro-parietal N400-like negativity and an anterior positivity.

Using the implicit learning paradigm applied in prior studies in the present tDCS study, we found no ERP learning effects in the learning-plus-test session irrespective of sham or cathodal stimulation. This null effect is in line with previous ERP studies with adults in a passive-listening learning paradigm (Mueller et al., 2009, 2012). It is, however, in contrast to a previous infant study that found an ERP learning effect in a passive listening learning-plus-test paradigm, identical to the present learning-plus-test session (Friederici et al., 2011). The observed difference between infants and adults for ERP learning effects during passive listening may be taken to suggest particular fast learning during infancy. In the present study, however, clear ERP learning effects were observed in the subsequent test-only session in which a grammaticality judgment was required. Moreover, in this session, behavioral learning could also be observed. These behavioral data indicate that successful learning took place independent of stimulation type and location. The finding that cathodal tDCS did not induce behavioral changes is in line with a recent met-analysis reporting a lack of cathodal effects on behavior viewed to reflect compensatory processes within the cognitive network (Jacobson, Koslowsky, & Lavidor, 2012). The differential ERP learning effects observed in the test-only session as a function of stimulation type and location, however, suggest that cathodal tDCS leads to changes in the mechanisms underlying learning.

In the test-only session, which required a grammaticality judgment, a significant centro-parietal N400-like negativity was found under sham stimulation. In the previous studies without any brain stimulation (Citron et al., 2011; Mueller et al., 2009), the observed N400-like negativity was interpreted to reflect lexically based learning mechanisms because the N400 is known to index lexical processes (Mueller et al., 2009; Lau et al., 2008; Chwilla et al., 1995). A lexically based learning mechanism in our paradigm could be the memorization of whole lexical forms such as "cantare" or "cantando." In the test-only session upon encountering a particular auxiliary, learners may have expected the correct lexical verb form that, when confronted with the incorrect form, leads to a difficulty in lexical integration, as expressed by the N400. The anterior positivity for the incorrect sentences, observed between 280 and 380 msec, is most likely a modulation of the P2 component, which typically occurs over anterior electrode sites and belongs, together with the N1 component, to the obligatory long-latency responses in the auditory-evoked potential (Crowley & Colrain, 2004). The P2 has been found to correlate with processes of stimulus classification during oddball tasks (Garcia-Larrea, Lukaszewicz, & Mauguiere, 1992; Novak, Ritter, & Vaughan, 1992) and, more recently, with rule detection processes during learning tasks (De Diego Balaguer, Toro, Rodriguez-Fornells, & Bachoud-Levi, 2007; Koester & Prinz, 2007). De Diego Balaguer et al. (2007) reported an increased P2 during initial stages of nonadjacent dependency learning, which they took to be an indicator of an attentional shift toward different (rule-based) stimulus properties. This is especially interesting for the interpretation of our findings. Note that, in contrast to earlier studies with the same stimulus material (Citron et al., 2011; Mueller et al., 2009), the adult participants first listened to correct as well as incorrect stimuli in the absence of a task and, only in the testing phase, received a grammaticality judgment task. This explains the comparatively low performance accuracy in this study (~68% vs. >86% in previous studies). If participants took all examples from the initial phase as correct examples (despite noticing that some of them were infrequent), they would have to reclassify the incorrect examples during the testing phase. We suggest that the P2 component in the sham condition represents this process of reclassification of the stimuli.

By using downregulating cathodal stimulation over the left PFC in the test-only session, the ERP data specifically revealed a learning effect reflected by a broadly distributed positivity between 650 and 900 msec after the onset of the verb suffix. This positivity resembles the positivity observed for infants in the same passive listening learning-plus-test paradigm (Friederici et al., 2011). The infant positivity was interpreted to reflect phonology-based learning mechanisms for 4-month-old presyntactic infants for which phonology is the only information available on the basis of which the dependency between the auxiliary and the main verb's suffix (*sta* verb-*ando*, *può* verb-*are*) can be learned (Friederici et al., 2011).[1] In contrast to the lexically driven processes indicated by the N400-like negativity, such phonological association processes allowing the learning of an auxiliary–suffix dependency can be considered as a kind of "rule processing," because the nonadjacent relation can only be built by abstracting over the intervening verb stem.

Downregulating stimulation over the right PFC leads to a tentative learning effect in the test-only session in the form of a late negativity, which, however, was not significant. The distribution of this N400-like negativity is similar, although delayed compared with the N400-like negativity observed under sham stimulation in this study. Interestingly, the downregulation of the right PFC leads to an absence of the anterior positivity (P2), which was observed under sham stimulation and interpreted as an indication of attention-dependent classification processes. Because the right PFC is taken to localize part of the attentional system (Corbetta & Shulman, 2002), the absence of this anterior positivity under the right PFC stimulation is in line with the view that the right PFC supports general attention-related processes in our task. Possibly, participants in the right PFC stimulation group were not aware that incorrect items were present during the initial learning phase and, thus, reclassification during the testing phase was not necessary. If this interpretation is valid, the present data suggest that the downregulation of attentional processes leads to delayed and less-efficient lexical processes reflected in a delayed and nonsignificant N400-like negativity.

With respect to the method applied in this study, it appears that it bears some limitations. Although tDCS has previously been shown before to be efficient in modulating brain functions across different domains, the spatial resolution is rather limited and the "reference" electrode is usually attached over the contralateral supraorbital region, thus potentially contributing to the effect. However, a recent meta-analysis suggested that the effects of tDCS might differ in motor and cognitive studies (Jacobson et al., 2012). Whereas, in motor studies, there is a clear polarity-dependent dissociation (anodal tDCS: facilitation, cathodal tDCS: inhibition) on behavioral and electrophysiological levels, this is not the case in the cognitive domain, where anodal tDCS still induces facilitation in most studies, but cathodal tDCS does not consistently result in an inhibition of a cognitive task, as measured by a behavioral change. The authors conclude that the lack of inhibitory cathodal effects on a behavioral level might reflect compensatory processes, because cognitive functions are typically supported by rich brain networks (Jacobson et al., 2012). Our data are in line with this notion. Although no inhibitory tDCS effect was observed on a behavioral level, the stimulation-induced modulation of the ERP reflected a change in learning strategy, pointing to a compensatory mechanism induced by the cathodal inhibition of PFC.

Conclusion

The present behavioral and neurophysiological data indicate that adult learning of nonadjacent dependencies in auditory language is possible irrespective of the downregulation of PFC but through different neurocognitive mechanism. Whereas the influence of cognitive control mediated by the left PFC leads to lexically based learning mechanisms as indicated by the N400-like negativity, phonologically based associative learning as indicated by the late positivity takes place when cognitive control is low.

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Note

1. In the previous publication (Friederici et al., 2011), we discussed the infant positivity in relation to the syntax-related positivity (P600). Here, we refrained from doing this because the present data provide good evidence that the two positivities are not reflecting the same process. The argument is the following: The P600 has been demonstrated to depend on cognitive control in that it varies under instruction (Hahne & Friederici, 2002). In this study, however, the positivity was absent under prefrontal control and showed up under the downregulation of PFC and, thereby, under less cognitive control. This could be taken as indirect evidence for a functional difference of the infant positivity and the P600.

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