Journal of Neurolinguistics 44 (2017) 239–248

Contents lists available at ScienceDirect

Journal of Neurolinguistics

journal homepage: www.elsevier.com/locate/jneuroling

The effects of transcranial direct current stimulation on pragmatic processing

Hagit Osovlanski [a], Nira Mashal [a, b, *]

[a] The School of Education, Bar-Ilan University, Ramat Gan, Israel
[b] Gonda Multidisciplinary Brain Research Center, Bar-Ilan University, Ramat Gan, Israel

ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 23 July 2017
Accepted 24 July 2017

Keywords:
tDCS
Pragmatics
Violation paradigm

ABSTRACT

The current study used the violation paradigm to assess responses to pragmatically and semantically violated sentences. Thirteen participants received bilateral tDCS stimulation (anodal – left Superior Temporal Gyrus (STG) and cathodal – right STG). The participants listened to sentences with no violations as well as sentences with pragmatic or semantic violations and had to indicate whether each sentence “makes sense”. This task was conducted in three conditions — without stimulation, after active stimulation, and after a sham procedure. The results showed faster response times for the pragmatic violations than for the semantic violations. The response times for the pragmatic violations after active stimulation were faster than after a sham stimulation. No similar difference in response times was observed for the semantic violations. These findings suggest that brain stimulation of the STG area modulates the processing of pragmatic but not semantic information.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Understanding the meaning of a sentence relies on the integration of semantic and pragmatic information. Semantic processing is based on the meaning of the words and considered purely linguistic. There are semantic rules which are applied in sentence comprehension. Verbs have selection restriction properties (Chomsky, 1965) which dictate the types of noun that may follow these verbs. While the sentence “I convinced my mother” makes sense, we will not accept the sentence “I convinced my number” because the semantic selection restriction properties of the verb “convince” (i.e., that the object must be a person) are incongruent with the object “number”. In contrast, pragmatics deals with the social aspects of communication. Pragmatic processing uses additional information that goes beyond the meaning of the words and is associated with knowledge about the world. In the current study, we use the term “pragmatic processing” in its narrow and specific sense, to refer to the use of “real world knowledge” to determine whether a sentence make sense (Kuperberg et al., 2000).

A well-established paradigm for studying semantic and pragmatic processing in sentence comprehension is the “violation paradigm”. In this paradigm, participants read or hear correctly formed sentences intermixed with sentences that contain some sort of violation or incongruity of syntax, semantics or pragmatics. Several studies have used the term “pragmatic violations” in the same way that the present study uses the term “real-world knowledge violations” (Kuperberg, Sitnikova, & Lakshmanan, 2008; Kuperberg, Sitnikova, Caplan, & Holcomb, 2003b; Kuperberg et al., 2003a; Marslen-Wilson, Brown, &

* Corresponding author. The School of Education, Bar-Ilan University, Ramat Gan, Israel.
E-mail address: mashaln@mail.biu.ac.il (N. Mashal).

http://dx.doi.org/10.1016/j.jneuroling.2017.07.002
0911-6044/© 2017 Elsevier Ltd. All rights reserved.

Tyler, 1988; Paczynski & Kuperberg, 2012; Ye & Zhou, 2009). Marslen-Wilson et al. (1988) were the first to use sentences with such violations. The participants listened to normal sentences (e.g., *John played the guitar*) and to sentences with syntactic (e.g., *John slept the guitar*), semantic (e.g., *John drank the guitar*), or pragmatic (*John buried the guitar*) violations, and had to press a computer key when they heard the target word (e.g. *guitar*). Each sentence was preceded by a lead-in sentence that provided a context for it. The results showed slower response times to the sentences with the violations than the normal sentences. The responses to sentences with pragmatic violations were significantly faster than to sentences with semantic violations. However, a different pattern of responses was documented in a later study (Kuperberg et al., 2008), in which the participants had to indicate whether a sentence they read "made sense". The participants responded to sentences with syntactic violations (e.g. *Every morning at breakfast the boys would eats toast and jam*), pragmatic violations (e.g., *Every morning at breakfast the boys would plant the flowers*) and sentences with semantic violations (e.g., *Every morning at breakfast the eggs would eat toast and jam*). The problem in the sentences with pragmatic violations lies at the level of integrating the occasions when boys might plant flowers with what we know about events that usually occur at breakfast. The sentences with semantic violations are ungrammatical because the inanimate subject "eggs" does not have the semantic attributes to perform the action of eating. When encountering such a violation one has to continue the analysis or the reanalysis of the critical word in relation to its context. The results showed that response times to sentences with pragmatic violations were significantly slower than to sentences with semantic violations. In addition, the response times to the semantically violated sentences did not significantly differ from those for the non-violated sentences. The different methods – i.e., the type of the word in which the violation could be detected (a noun vs. a verb), the presence of a lead-in sentence, the location of the target word within the sentence and the type of task – may have contributed to the apparently contradictory results.

Evidence for behavioral differences in processing semantic and pragmatic violations were also observed in studies using other techniques. For instance, eye-movement tracking studies (Rayner, Warren, Juhasz, & Liversedge, 2004; Warren & McConnell, 2007) showed a difference in eye-movement patterns when people read sentences with semantic or pragmatic violations. Paczynski and Kuperberg (2012) found different event-related potential (ERP) waveforms for semantic and pragmatic violations. Both types of violations elicited an N400 waveform in response to the critical word. The N400 waveform is a negative-going potential with an onset at about 250 ms and a peak around 400 ms and is thought to reflect the semantic processing of a word in relation to its preceding context (Kutas & Federmeier, 2011). The semantic associates of the critical word in the preceding linguistic context attenuated the N400 response to the world-knowledge violations but did not attenuate the N400 response to the semantic violations. Those findings suggest that the brain distinguishes between the processing of real-world knowledge and semantic (selection-restriction) information during sentence comprehension.

Neuroimaging studies of pragmatic and semantic violations yielded inconsistent findings (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Kuperberg et al., 2008, 2000; Menenti, Petersson, Scheering, & Hagoort, 2009; Tesink, Buitelaar & Petersson, 2011; Ye & Zhou, 2009). Kuperberg et al. (2000) measured the neural activity of subjects listening to normal sentences in contrast to sentences containing pragmatic, semantic or syntactic violations. The participants were asked to judge whether the sentences "made sense". The violations were created by replacing the last word of the normal sentences (e.g., *My mother ironed a shirt*) with one that created a syntactic violation (e.g., *His father chattered the umbrella*), semantic violation (e.g., *My mother ironed a kiss*) or a pragmatic one (e.g., *The woman painted the insect*). Greater activation in the left superior-temporal gyrus (STG) was observed for the pragmatic condition than for either the normal, the semantic or the syntactic one, and there was greater activation of the right STG and middle-temporal gyrus (MTG) in the semantic than in the syntactic condition. A subsequent study compared the brain activity of subjects reading normal sentences or tones with syntactic or pragmatic violations (Kuperberg et al., 2003a). In that study the word creating the violation was a verb which was sentence-final (e.g. *for good photographs we hoped that the infant would phone*) or non-sentence-final (e.g. *If the post office is closed John cannot shoot the letter*). Greater activity in the left STG was found in response to sentences with pragmatic violations than to those with syntactic ones, as well as in the adjacent STS when sentences with pragmatic violations were compared with normal ones (this study did not include sentences with semantic violations). These studies thus suggest that the left STG may play an important role in processing sentences with pragmatic violations. However, inconsistent findings were observed in a later study that tested the neural correlates of normal sentences and those with syntactic, semantic or pragmatic violations (Kuperberg et al., 2008). The findings revealed greater activity in the left anterior inferior frontal gyrus (IFG) and the bilateral anterior ventromedial temporal cortices (fusiform and parahippocampal gyri) in response to real-world violations than to each of the other three sentence types. The stimuli used in this study were similar to those of the previous study (Kuperberg et al., 2003a), and the word creating the violation was a verb that was not sentence-final. The above studies thus demonstrate increased activity in the left STG when processing pragmatic violations where the target word is at the end of the sentence. In contrast, processing pragmatic violations in which the critical word is a verb or not necessarily sentence-final yields inconsistent results.

Tesink et al. (2011) reported different results. The participants listened to normal sentences (e.g. Dutch trains are *yellow* and blue), sentences containing semantic violations ("Dutch trains are sour and blue"), and sentences with pragmatic world-knowledge violations ("Dutch trains are white and blue"). In this study, the sentences with the pragmatic violations have coherent semantic interpretations but are false. The findings showed greater activity in the left STG and the left IFG for the sentences with the semantic violations than for the normal sentences, but when the sentences with the pragmatic violations were compared to normal ones, the increased activity was seen bilaterally in the IFG but not in the STG area. Direct comparisons between sentences with pragmatic and semantic violations were not reported. Perhaps the use of different type of pragmatic violations may explain the different results.

Given the paucity of studies that directly compared sentences with semantic and pragmatic violations, the current study tested whether the processing of real-world knowledge can be modulated by transcranial Direct Current Stimulation (tDCS) over the left STG. tDCS is a non-invasive, painless, safe brain stimulation technique (Nitsche et al., 2008) which utilizes a persistent direct current. The current is passed between a positively charged anode and a negatively charged cathode placed over the scalp. Depending on the polarity of the current flow, brain excitability can be either increased or decreased. Anodal stimulation is considered to produce an enhancement of cortical excitability, while cathodal stimulation appears to have the opposite effect (Nitsche & Paulus, 2000), both during stimulation and for a few minutes thereafter. The stimulating electrode is placed over the target area and the second (reference) electrode may be placed over a remote region in unilateral stimulation or over the contralateral area in bilateral stimulation. Recent evidence suggests that tDCS over the left STG affects language performance, probably by facilitating lexical processes via pre-activation of language-related neural networks (Sparing, Dafotakis, Meister, Thirugnanasambandam, & Fink, 2008). For instance, Sparing et al. (2008) demonstrated that a unilateral anodal tDCS to the left STG area enhanced performance on a picture-naming task. Participants responded significantly faster following a unilateral anodal tDCS to the left STG than after a unilateral cathodal stimulation to that area, anodal stimulation to the homologue area, or a sham procedure. STG stimulation also enhances verbal associative learning by applying anodal stimulation over Wernicke's area (Fiori, Cipollari, Caltagirone, Marangolo, 2014; for review see Hartwigsen, 2015). Nevertheless, it should be noted that our present understanding of tDCS limits the technique's ability to localize function in the human brain (De Berker, Bikson & Bestmann, 2013). As such, the effects of tDCS are not restricted to the stimulation site but rather, it can induce changes at distant points through effective modulations of remote, interconnected networks (e.g., Hummel & Cohen, 2006).

Several studies tested the effects of bilateral tDCS instead of unilateral stimulation on cognitive performance. For example, Lifshitz Ben Basat, Gvion, Vatine, and Mashal (2016) found that bilateral tDCS stimulation over language areas improves the naming abilities of individuals with chronic aphasia. Metzuyanim-Gorlick and Mashal (2016) found that bilateral tDCS over the dorsolateral prefrontal cortex (DLPFC) (anodal over left and cathodal over right DLPFC) improved cognitive inhibition in healthy participants. Furthermore, there is evidence suggesting that bilateral stimulation facilitates motor performance more than unilateral stimulation (Mordillo-Mateos et al., 2012; Sehm, Kipping, Schafer, Villringer, & Ragert, 2013; Vines, Cerruti, & Schlaug, 2008). It has been also shown that bilateral stimulation of the motor cortex induces an increase in cortical excitability on the anodal-stimulated side and a decrease in the cathodal-stimulated side (Mordillo-Mateos et al., 2012). However, the effects of bilateral as compared to unilateral stimulation on cognitive functioning are still unclear. Nevertheless, Boggio et al. (2009) showed that anodal tDCS to the left anterior temporal lobe (ATL) reduced false memories while maintaining veridical memory performance. The anodal stimulation was performed in two ways, unilateral stimulation of the left ATL and bilateral (anodal left/cathodal right ATL) stimulation. Both unilateral and bilateral tDCS were effective in reducing false memories. However, the magnitude of effect after bilateral stimulation, although not significant was larger than that of the unilateral stimulation.

The aim of the current study was to investigate the effects of tDCS over the STG area on pragmatic processing. We used sentences similar to those of Kuperberg et al. (2000). The participants listened to normal sentences and to sentences with either semantic or pragmatic violations and were asked whether the sentences "made sense". The word producing the violation was a sentence-final noun. We hypothesized that sentences with pragmatic violations would be processed faster than those with semantic violations. We also hypothesized that bilateral stimulation of the left STG area (anode electrode over left STG, cathode electrode over right STG) would improve the response times to the sentences with the pragmatic violations but not those with the semantic violations.

2. Methods

The study included a tDCS experiment which was preceded by an online pre-test intended to validate the stimulus pool.

3. Online pre-test

To validate the three sentence types, an online pre-test was conducted to test for differences among the three conditions.

3.1. Participants

Ten native Hebrew speakers took part in the online pre-test (5 men and 5 women; mean age = 48.45, SD = 4.78, range 41–54 years). Vocabulary knowledge was assessed by a Hebrew version of the Peabody Picture Vocabulary Test (PPVT-4 (Dunn & Dunn, 2007)). The mean score was 74.6 (out of 84), SD = 7.83. No other cognitive performance measures were performed.

3.2. Stimulus construction

The initial stimulus pool consisted of 195 sentences in Hebrew – 65normal sentences, 65 sentences with pragmatic violations, and 65 with semantic violations. The sentences with the pragmatic and the semantic violations were created by replacing the last word of a normal sentence with a word creating a violation. These sentences were submitted to 10 native

Hebrew speakers (aged 20–55) for an offline pre-test. These individuals were asked to fill out a questionnaire in which they had to use plus or minus signs to indicate whether each sentence described a possible situation, and whether the sentence described a reasonable situation which could occur in real life. Sentences that were rated by at least 90% of the judges as describing a possible and reasonable situation were selected to be used as normal sentences (e.g., *At dinner my uncle drank juice*). Sentences that were rated by at least 90% of the judges as describing an impossible (and thus unreasonable) situation were selected to be used as sentences with semantic violations (e.g., *At dinner my uncle drank a rock*). Sentences that were rated by at least 90% of the judges as describing possible but unlikely situations were selected to be used as sentences with pragmatic violations (e.g., *At dinner my uncle drank gasoline*). The final stimulus pool thus consisted of 50 normal sentences, 50 sentences with pragmatic violations and 50 with semantic violations. The sentence-final words contained 1–3 syllables, their frequency ranging from 59 to 64375 (per million). Word frequency was assessed through the Hebrew word frequency database (Linzen, 2009). The final words were balanced among the three conditions according to word frequency and number of syllables. A one-way ANOVA with sentence type found no significant difference in either the frequency rate $F(2,147) = 1.49$, $p = 0.23$, or the number of syllables $F(2,147) = 1.47$, $p = 0.86$, indicating no significant differences in either attribute among the lists. The sentences without the final words (sentence preambles) were recorded by a native adult female Hebrew speaker (in her fifties). The final words were recorded separately by the same speaker and were spliced into the sentence preambles.

3.3. Procedure

The participants attended a session at which their vocabulary knowledge was assessed by the PPVT test. They were then told that they would hear a series of sentences and were instructed to judge whether each sentence "makes sense" by pressing one of two keys using their dominant hand ("b" for "makes sense" and "n" for "does not make sense"). The participants sat in front of the computer and heard the sentences via headphones connected to the computer. First they heard the sentence without the final word, and then they heard the final word. While each sentence was being played, the participants saw a blank white screen. A fixation mark was presented at the middle of the screen for a fixed time of 3 s between one sentence and the next to allow enough time to answer. The order of the sentences was randomized. The sentences were played via Cedrus SuperLab version 5.0 software (Cedrus Corp, San Pedro, CA), which also recorded the response times and accuracy. The experiment started with a practice list of six sentences (two of each type).

3.4. Results

Table 1 presents the reaction times (RTs) and the accuracy rate for each sentence type. The RTs were analyzed with a one-way repeated measure analysis of variance (ANOVA), with sentence type as the within-subject factor (three levels: normal sentence, sentence with a pragmatic violation, sentence with a semantic violation). Reaction times that exceeded 2 standard deviations from the participant's mean for each sentence type were excluded. Overall, 4.99% of the trials were excluded. Only the correct trials were analyzed. Error rates were too low to permit meaningful analyses (see Table 1) and therefore, the accuracy data was not analyzed.

The RT analysis yielded a significant effect of sentence type, $F(2, 18) = 3.92$, $p = 0.04$, $\eta^2 = 0.30$. Bonferonni adjusted post-hoc comparisons revealed that RTs to normal sentences did not significantly differ from RTs to sentences with pragmatic violations, $p = 0.49$, or sentences with semantic violations, $p = 0.89$. Sentences with pragmatic violations were processed significantly faster than sentences with semantic violations, $p = 0.04$.

4. tDCS experiment

4.1. Participants

Thirteen right-handed, native-Hebrew-speaking volunteers took part in the experiment (6 men and 7 women; mean age 49.15, $SD = 4.65$ range 38–54 years). Their receptive vocabulary was assessed by the Hebrew version of the Peabody Picture Vocabulary Test (PPVT-4 (Dunn & Dunn, 2007)); their mean score was 74.85 (out of 84), $SD = 3.26$. No other cognitive performance measures were taken. People with a history of seizures or neurological or psychiatric diagnoses were excluded from the study. The participants gave informed consent and the ethics committee of the School of Education of Bar-Ilan

Table 1
Reaction times and accuracy rate (and SD) per sentence type in the pre-test.

Sentence Type	Reaction Times		Accuracy	
	M	SD	M	SD
Normal	1712.75	117.40	99.2	1.03
Pragmatic violations	1678.36	158.89	91.8	7.91
Semantic violations	1735.059	133.133	97.6	2.27

University approved the study, which was conducted in adherence to the Helsinki Declaration. All the participants took part in the active stimulation as well as the sham session.

4.2. Stimuli

The stimuli included 144 Hebrew sentences (48 normal sentences, 48 sentences with pragmatic violations, and 48 with semantic violations) derived from the online pre-test, with two sentences omitted from each condition. Sentences for which four or more participants in the online pre-test (86.67% of the participants) gave the wrong answer were excluded. The sentences were divided into three lists for each stimulation condition (baseline, active stimulation, sham). Each list consisted of 48 sentences − 16 normal sentences, 16 sentences with pragmatic violations, and 16 with semantic violations.

The same sentence preambles did not appear twice in the same list. The lists were counterbalanced by the number of syllables (1–3) and the frequency of the final word. The word frequency was taken from the Hebrew word frequency database (Linzen, 2009). A two-way ANOVA, 3 (sentence type: normal, with pragmatic violations, with semantic violations) x 3 (stimulation condition: baseline, active tDCS, sham stimulation) on the frequency rate showed no significant main effect of sentence type, $F\ (2{,}135) = 1.44$, $p = 0.24$, $\eta^2 = 0.02$, stimulation condition, $F\ (2{,}135) = 0.51$, $p = 0.61$, $\eta^2 = 0.01$, or the interaction between the two, $F\ (2{,}135) = 0.07$, $p = 0.99$, $\eta^2 = 0.00$, indicating no significant differences in word frequency among the lists. Similarly, the two-way ANOVA(sentence type x stimulation condition) on the number of syllables showed no significant main effect of sentence type, $F\ (2{,}135) = 1.47$, $p = 0.86$, $\eta^2 = 0.00$, stimulation condition, $F\ (2{,}135) = 0.78$, $p = 0.46$, $\eta^2 = 0.01$, or the interaction between the two, $F\ (2{,}135) = 1.06$, $p = 0.38$, $\eta^2 = 0.03$, indicating no significant differences in the number of syllables in the final word among the lists.

4.3. tDCS

The tDCS was delivered by a battery-driven, constant-current stimulator (neuro-Conn GmbH, Ilmenau, Germany) using a pair of surface saline-soaked sponge electrodes (5 cm × 5 cm). The sponges were placed over CP5 and CP6 scalp positions (according to the EEG 10–20 system) and were kept in place by elastic bands. These positions were correlated with the left and right STG areas, respectively (Sparing et al., 2008; Weltman & Lavidor, 2013). A 10–20 EEG cap was used to mark the correct location for the electrode placement. Bilateral tDCS stimulation was applied by placing the anode electrode over the left STG area and the cathode electrode over the right STG area (see Fig. 1). In the active stimulation condition, a constant current of 2 mA was applied for 20 min with a ramping period of 30 s both at the beginning and at the end of the stimulation. Sham stimulation was performed in the same way, although the current was stopped automatically after the first 30 s. This procedure reliably blinds subjects for the respective stimulation condition (Gandiga, Hummel, & Cohen, 2006).

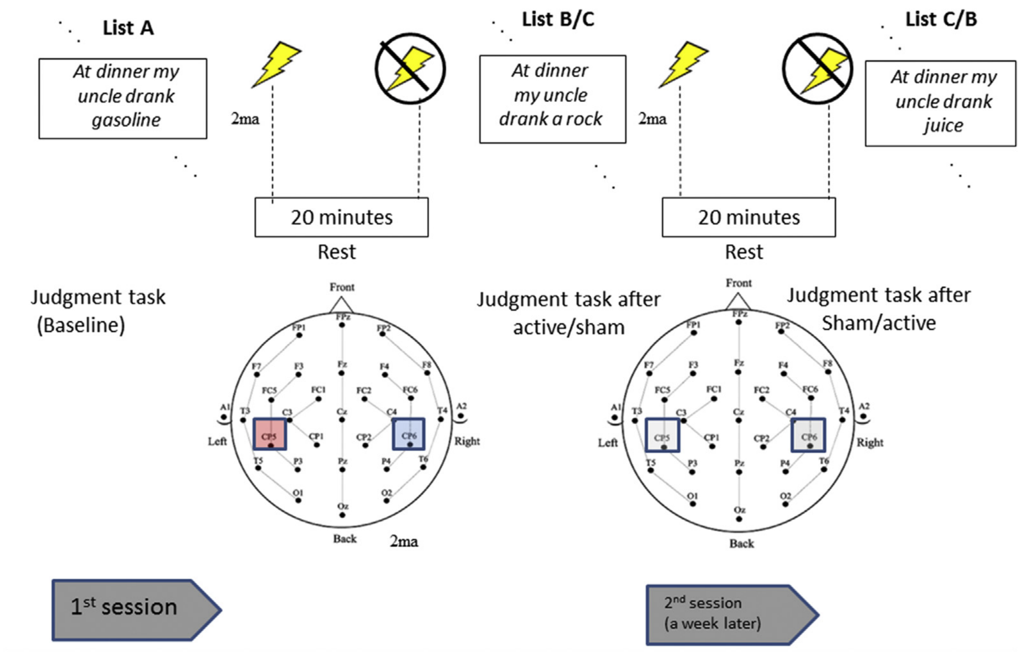

Fig. 1. Schematic representation of the study design presenting an example of a sentence with pragmatic violation, semantic violation and a normal sentence (from left to right) and the tDCS montage. See text for full details.

4.4. Procedure

The participants attended two sessions. In the first session, after completing the PPVT (Dunn & Dunn, 2007), they participated in the baseline condition, in which they listened to all the sentences in the first list and performed a behavioral judgment task. The participants sat in front of the computer and heard the sentences in a woman's voice via headphones connected to the computer. While the sentence was playing, the participants saw a blank white screen. A fixation mark was presented at the middle of the screen for a fixed time of 3 s between one sentence and the next to allow the user enough time to answer whether it described a "reasonable" situation by pressing one of two keys using their right hand ("b" for "reasonable" and "n" for "unreasonable"). The order of the sentences was randomized. After 20 min of stimulation the participants listened to another list of sentences and performed the same judgment task again. Six participants were given active stimulation and seven sham stimulation.

The second session took place one or two weeks after the first and included 20 min of stimulation, after which the participants performed the task on the third list. Those who participated in the active tDCS stimulation in the first session underwent sham stimulation in the second session and vice versa (See Fig. 1).

Overall, each participant performed the judgment task in 3 conditions – no stimulation, active stimulation and sham stimulation (with the order of active and sham stimulation counterbalanced). The tDCS application was single-blinded as the participants were told in advance that they are going to receive two sessions of brain stimulation. The participants reported a tingly or itchy sensation at the start of the stimulation (both in the sham and the active condition), which typically faded away. After debriefing, the participants reported that they could not feel any difference in the sensation between the sessions.

4.5. Results

Fig. 2 and Table 2 present the reaction times and accuracy data for each sentence type as a function of stimulation condition. Reaction times that exceeded 2 standard deviations from the participant's mean for each sentence type were excluded. Overall, 4.30% of the trials were excluded. Only correct trials were analyzed. Error rates were too low to permit meaningful analyses (see Table 2), therefore, the accuracy data was not analyzed.

The data were initially analyzed with 3 (sentence type: normal, with pragmatic violations, with semantic violations) x 3 (stimulation condition: baseline, active stimulation, sham stimulation) x 2 (order of stimulation: tDCS in the first session, tDCS in the second session) repeated-measure ANOVA. The main effect of order of stimulation, $F(1, 11) = 0.35$, $p = 0.67$, $\eta^2 = 0.03$, was non-significant. The RT analysis indicated non-significant interactions with order of stimulation: order and sentence type $F(2, 22) = 2.92$, $p = 0.10$, $\eta^2 = 0.27$; order and condition $F(2, 22) = 1.46$, $p = 0.26$, $\eta^2 = 0.12$; order, sentence type and condition, $F(4, 44) = 0.14$, $p = 1.00$, $\eta^2 = 0.01$. The analyses were therefore conducted without the factor of order.

A two-way 3 × 3 repeated-measures ANOVA with 3 sentence types (normal, with pragmatic violations, with semantic violations) and 3 stimulation conditions (baseline, active tDCS, sham stimulation) as within-subject factors were performed for response times as dependent variable.

4.6. Reaction times

The RT analysis indicated a significant main effect of sentence type, $F(2, 24) = 16.05$, $p < 0.001$, η2 = 0.57. Bonferonni adjusted post-hoc comparisons revealed that the responses to normal sentences ($M = 1721.25$, $SD = 188.79$) were

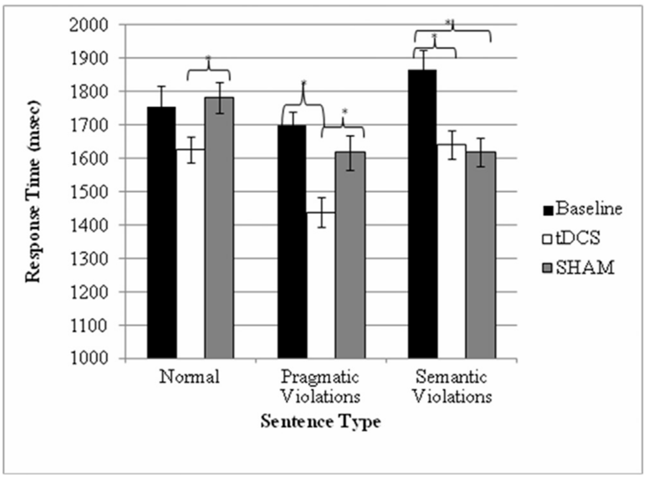

Fig. 2. Mean reaction times (standard errors) by sentence type and stimulation condition.

Table 2
Percent of correct responses and SD for sentence type by stimulation conditions.

Sentence Type	Baseline		Active stimulation		Sham stimulation	
	M	SD	M	SD	M	SD
Normal	100	0.00	98.08	3.00	96.63	4.85
Pragmatic violations	94.71	5.62	98.08	3.00	98.08	3.94
Semantic violations	98.56	2.74	98.56	2.74	100.00	0.00

significantly slower than the responses to sentences with pragmatic violations ($M = 1610.49$, $SD = 177.50$), $p = 0.003$, and did not significantly differ from RTs to sentences with semantic violations ($M = 1708.37$, $SD = 204.70$), $p = 1.00$. RTs to sentences with pragmatic violations were significantly faster than RTs to sentences with semantic violations, $p < 0.001$.

The RT analysis also indicated a significant main effect of stimulation condition, $F\,(2, 24) = 14.68$, $p < 0.001$, $\eta^2 = 0.55$. Bonferonni adjusted post-hoc comparisons revealed that RTs in the baseline condition ($M = 1772.30$, $SD = 193.11$) were significantly slower than after active tDCS stimulation ($M = 1595.02$, $SD = 155.34$), $p < 0.001$, but did not significantly differ from RTs after sham stimulation ($M = 1672.79$, $SD = 185.90$), $p = 0.11$. In addition, RTs after active tDCS stimulation were significantly faster than for sham stimulation, $p = 0.01$.

The two-way interaction of sentence type x stimulation condition was significant, $F\,(4, 48) = 8.83$, $p < 0.001$, $\eta^2 = 0.42$. For normal sentences, Bonferonni adjusted post-hoc comparisons revealed faster response times in the active stimulation than in the sham condition, $p > 0.001$. Non-significant differences were found between the baseline and the active stimulation, $p = 0.07$, and between the baseline and the sham condition, $p = 1.00$. For sentences with pragmatic violations, response times were faster after active stimulation than at baseline, $p < 0.001$. No significant difference was found between RTs after sham stimulation as compared to the baseline condition, $p = 0.29$. Importantly, RTs in the active stimulation condition were significantly faster than in the sham condition, $p = 0.03$. For sentences with semantic violations, RTs in the baseline condition were significantly slower than RTs after active stimulation, $p < 0.001$, and after sham stimulation, $p = 0.005$. No significant difference in response times was found between the active and the sham stimulation, $p = 1.00$.

To summarize, the main findings indicate faster response times to sentences with pragmatic violations following active stimulation than following a sham session. Response times were also faster following active stimulation than for the baseline. However, response times to semantically violated sentences following active stimulation did not differ from the sham condition (see Fig. 2).

4.7. Comparing pragmatically and semantically violated sentences at baseline

Finally, to corroborate the results of the on-line pre-test that sentences with pragmatic violations are processed faster than those with semantic violations, we analyzed the reaction times at baseline condition (Table 3) with a one-way repeated-measures ANOVA, with sentence type as the within-subject factor (three levels: normal sentences, sentences with pragmatic violations, sentences with semantic violations). The RT analysis yielded a significant effect of sentence type, $F(2, 24) = 9.39$, $p = 0.004$, $\eta^2 = 0.44$. Bonferonni adjusted post-hoc comparisons revealed that RTs for normal sentences did not differ significantly from sentences with pragmatic violations, $p = 0.81$, but were significantly faster than RTs for sentences with semantic violations, $p = 0.02$. Pragmatically violated sentences were processed significantly faster than those with the semantic violations, $p < 0.001$.

5. Discussion

In the current study we used the semantic/pragmatic violation paradigm to investigate how tDCS affects sentence comprehension and specifically pragmatic processing. Participants listened to normal sentences and to sentences with either semantic or pragmatic violations in which the word that violated the rule was sentence-final and had to judge whether those sentences made sense. The tDCS experiment revealed that the responses to sentences with pragmatic violations were faster after active bilateral stimulation of the left STG (anodal-left STG, cathodal-right STG) area than after sham stimulation. However, active stimulation did not affect the response times to the sentences with semantic violations. Additionally, the results showed that sentences with pragmatic violations were processed faster than those with semantic violations.

Our results indicate faster response times to sentences with pragmatic violations than those with semantic violations in both the online pre-test and the baseline condition of the tDCS experiment. These findings are consistent with those of

Table 3
Reaction times and SD for sentence type at the baseline condition.

Sentence Type	M	SD
Normal	1754.10	223.27
Pragmatic violations	1697.70	148.96
Semantic violations	1865.10	210.33

Marslen-Wilson et al. (1988), who also reported faster responses to sentences with pragmatic violations than to those with semantic violations. Although those findings may be task- and stimulus-dependent, as discussed in the introduction, our results support the view that language comprehension rapidly takes account of the social context, which is processed by the same early interpretation mechanism that constructs sentence meaning based on the semantics of the words (Van Berkum, Van den Brink, Tesink, Kos, & Hagoort, 2008). In contrast to this view, classic two-step models of sentence comprehension (Grice, 1975) claim that comprehenders initially compute a local, context-independent meaning for the sentence (semantics) before working out what it really means within the broader communicative context and the speaker's intent (pragmatics). However, our findings do not support this serial two-step approach, as they show faster access to social than semantic information.

As predicted, bilateral stimulation of the left STG area improved the processing of pragmatic violations. The participants processed the pragmatic violations faster after active stimulation than after sham stimulation. Those findings may suggest that bilateral left anodal tDCS over the STG may improve pragmatic processing. Consistent with previous studies showing that bilateral stimulation enhances the cognitive function of the target area (Jacobson, Koslowsky, & Lavidor, 2012), we suggest that anodal left STG stimulation modulates pragmatic processing during sentence comprehension. However, because the effect of tDCS is not restricted to the stimulation site (Hummel & Cohen, 2006) the causal role of the STG in pragmatic processing is still not clear and should be tested in future studies. Although this was not tested in the current study, based on a previous study (Weltman & Lavidor, 2013) it can be speculated that applying the opposite montage (i.e., right anodal/left cathodal), may impair the processing of the sentences with pragmatic violations. Weltman and Lavidor (2013) found impaired lexical processing under right anodal/left cathodal over the STG in comparison with sham and left anodal/right cathodal stimulation. The authors concluded that the cathodal stimulation to the left side simultaneously with the anodal stimulation to the right side interrupted the typical lexical processing dominance of the left hemisphere.

Our findings are consistent with previous fMRI studies (Kuperberg et al., 2000, 2003a), which showed greater activation in the left STG for sentences with pragmatic violations than for normal sentences, which suggests a significant involvement of this area in processing real-world knowledge. Kuperberg et al.'s; (2000) study was composed of three different experiments in which blocks of normal sentences were alternated with blocks of either pragmatically, semantically or syntactically violated sentences. No direct comparison was performed between sentences with pragmatic violations and semantic violations. However, planned comparisons between the experiments revealed a greater difference between conditions with left STG activation for the pragmatic experiment than for the other two experiments. Our study directly compared responses to pragmatically and semantically violated sentences and found different responses to these sentence types upon STG stimulation.

The response times to the sentences with semantic violations after active tDCS stimulation did not differ from those for the sham stimulation, suggesting that the stimulation did not affect the processing of the semantic violations. This finding corroborates with previous fMRI studies (Hagoort et al., 2004; Kuperberg et al., 2000), which did not find greater activity in the left STG area for sentences with semantic violations than for normal sentences. Whereas Hagoort et al. (2004) found increased activation in the left inferior prefrontal cortex (LIPC), Kuperberg et al. (2000) showed that the right-superior and the middle-temporal gyri were more activated in response to semantic violations than for normal sentences. However, other studies (Friederici, Rüschemeyer, Hahne, & Fiebach, 2003; Kuperberg et al., 2008; Ni et al., 2000) did find greater activation in the left STG for sentences with semantic violations than for normal sentences. There were, however, some methodological differences between these three studies and the present study. Two of the studies (Friederici et al., 2003; Ni et al., 2000) did not include sentences with pragmatic violations. The participants in Ni et al.'s (2000) study did not perform a semantic judgment task but rather had to decide whether the sentence included a noun referring to an animate object. In addition, some of the target words were verbs. The sentences used by Friederici et al. (2003) were in the imperfect passive mode and the target words were verbs, as in Kuperberg et al. (2008). In the current study all the target words which created the violations were nouns. It seems that the type of word (noun vs. verb) affects the comprehension process, as the neural bases obtained from studies using verbs as target words differ from those in studies using nouns as target words. These methodological differences may explain the contradictory results. Future studies are required to explore the effects of the target word type, its location within the sentence, the syntactic complexity of the sentence and the task on the activity in the left STG.

The current study used a target word which was both sentence-final and a noun. However, the involvement of the STG in processing sentences containing semantic violations in which the target words are verbs is still not clear. Our findings point to facilitation of pragmatic processing but not of semantic processing following STG stimulation. Given the prominent role of the STG in processing sentences containing semantic violations in which the target words are verbs (Friederici et al., 2003; Kuperberg et al., 2008; Ni et al., 2000), it is important to further conduct brain stimulation studies to disentangle the role of the STG in processing sentences with violations. Furthermore, future studies should investigate the causal role of the left STG in comparison to the left IFG, given the evidence pointing to greater activity in the left IFG in response to sentences with semantic violations than for normal sentences (Kuperberg et al., 2008; Tesink et al., 2011).

The results also show that normal sentences, but not sentences with violations, were processed faster after the active than after the sham stimulation. This finding is consistent with fMRI studies (Friederici et al., 2003; Kuperberg et al., 2000) which found activity in the bilateral superior temporal gyri during the processing of normal sentences. The left STG area includes Wernicke's area, which is associated with language comprehension (Démonet, Thierr, & Cardebat, 2005). Brain damage in this area affects language comprehension. Therefore, stimulation of the left STG may improve the processing of normal sentences.

Marslen-Wilson et al. (1988) claimed that a sentence with a pragmatic violation can easily be turned into a normal sentence if the right context is provided. One can easily find a context in which the sentence "John buried the guitar" would make sense, but the sentence "John drank the guitar" can never make sense. This similarity between normal sentences and sentences with pragmatic violations can also explain the similarity in the results.

Sentences with semantic violations were processed faster after both the active and the sham stimulation than in the baseline condition. The semantic violations were processed significantly slower at baseline (1865.10 ms) than both the pragmatic violations (1697.70 ms) and the normal sentences (1754.10 ms). Thus the participants had the chance to improve their performance on repeating the task after both the active stimulation and the sham stimulation. If the real (active) stimulation itself affected the processing of the semantic violations, we would have seen faster response times after the active than the sham condition. However, no difference was observed between the two stimulation conditions. In contrast, the response times of the sentences with pragmatic violations were initially faster than those with semantic violations at baseline, and nevertheless, participants improved their performance after active and not sham stimulation. Although only the first session included the baseline, half of the participants got the active stimulation in the first session, right after the baseline task, and the other half got the active stimulation in the second session (when there was no baseline). Nevertheless, we demonstrated that the order of the tasks did not affect performance and thus the comparison between the active and the sham conditions is valid (because the order of the tasks in the sessions also indicates whether or not the baseline was conducted at the same session as the active tDCS). Notably, tDCS stimulation did not affect the accuracy rate for the three sentence types, probably because of the high rate at baseline (ranging from 94.8% to 100%). Thus, only improvement in response times for pragmatic violations emerged in the current study. It would be interesting to repeat this study with a more difficult task to see whether tDCS can improve accuracy rate as well.

Some limitations of this study should be mentioned. First, the number of normal sentences was equal to both the number of sentences with pragmatic violations and those with semantic violations, so that the ratio of correct to incorrect sentences was 1:2. Thus, subjects may have been biased by the need to press "does not make sense" twice as often as "makes sense". Such a bias may explain why the sentences with the pragmatic violations were processed faster than the normal sentences in the pre-test. Thus, although the pragmatically and the semantically violated sentences had a ratio of 1:1, which allowed for a valid comparison between them, future studies should use a 1:1 ratio between normal sentences and sentences with violations. Second, we used a rather small sample size of 13 participants and no power analysis was conducted prior to the study. Further study is required to reinforce the results with more participants.

6. Conclusions

To conclude, our study points to behavioral and anatomical differences in processing sentences with semantic or pragmatic violations. The differences include faster responses to pragmatic violations than to semantic violations. The fact that the tDCS decreased the response times only for the pragmatic violations indicates that it alters pragmatic (but not semantic) processing when applied over the left STG. Our findings may also point to different brain mechanisms underlying semantic and pragmatic comprehension, probably because the brain uses real-world information differently from semantic information when it constructs the meaning of a sentence. It seems that semantic processing relies on additional processes such as integrating words from remote semantic fields (e.g. "drinking" and "solid") and checking whether the selection restrictions are met. These processes probably recruit other brain areas (e.g., frontal brain regions). Given the difficulties in using and processing pragmatic information among individuals with autism, schizophrenia and learning disorders, future studies are need to investigate whether tDCS improves pragmatic processing and other aspects of pragmatics (e.g., understanding figurative language) among these individuals with pragmatic impairments.

References

Boggio, P. S., Fregni, F., Valasek, C., Ellwood, S., Chi, R., Gallate, J., … Snyder, A. (2009). Temporal lobe cortical electrical stimulation during the encoding and retrieval phase reduces false memories. *PLoS One, 4*(3), e4959.

Chomsky, N. (1965). *Aspects of the theory of syntax*. Cambridge, MA: MIT Press.

De Berker, A. O., Bikson, M., & Bestmann, S. (2013). Predicting the behavioral impact of transcranial direct current stimulation: Issues and limitations. *Frontiers in Human Neuroscience, 613*(7). http://dx.doi.org/10.3389/fnhum.2013.00613.

Démonet, J. F., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: Functional neuroimaging. *Physiological Reviews, 85*(1), 49–95.

Dunn, D. M., & Dunn, L. M. (2007). *Peabody picture vocabulary test* (4th ed.). Minneapolis: Pearson.

Fiori, V., Cipollari, S., Caltagirone, C., & Marangolo, P. (2014). If two witches would watch two watches, which witch would watch which watch? tDCS over the left frontal region modulates tongue twister repetition in healthy subjects. *Neuroscience, 256*, 195–200.

Friederici, A. D., Rüschemeyer, S. A., Hahne, A., & Fiebach, C. J. (2003). The role of left inferior frontal and superior temporal cortex in sentence comprehension: Localizing syntactic and semantic processes. *Cerebral Cortex, 13*(2), 170–177.

Gandiga, P. C., Hummel, F. C., & Cohen, L. G. (2006). Transcranial DC stimulation (tDCS): A tool for double-blind sham-controlled clinical studies in brain stimulation. *Clinical Neurophysiology, 117*(4), 845–850.

Grice, P. (1975). Logic and conversation. In P. Cole, & J. L. Morgan (Eds.), *Syntax and semantics 3: Speech acts* (pp. 41–58). New York: Seminar Press.

Hagoort, P., Hald, L., Bastiaansen, M., & Petersson, K. M. (2004). Integration of word meaning and world knowledge in language comprehension. *Science, 304*(5669), 438–441.

Hartwigsen, G. (2015). The neurophysiology of language: Insights from non-invasive brain stimulation in the healthy human brain. *Brain and Language, 148*, 81–94.

Hummel, F. C., & Cohen, L. G. (2006). Non-invasive brain stimulation: A new strategy to improve neurorehabilitation after stroke? *Lancet Neurology, 5*, 708–712. http://dx.doi.org/10.1016/s1474-4422(06)70525-7.

Jacobson, L., Koslowsky, M., & Lavidor, M. (2012). tDCS polarity effects in motor and cognitive domains: A meta-analytical review. *Experimental Brain Research, 216*(1), 1–10.

Kuperberg, G. R., Holcomb, P. J., Sitnikova, T., Greve, D., Dale, A. M., & Caplan, D. (2003a). Distinct patterns of neural modulation during the processing of conceptual and syntactic anomalies. *Journal of Cognitive Neuroscience, 15*(2), 272–293.

Kuperberg, G. R., McGuire, P. K., Bullmore, E. T., Brammer, M. J., Rabe-Hesketh, S., Wright, I. C., … David, A. S. (2000). Common and distinct neural substrates for pragmatic, semantic, and syntactic processing of spoken sentences: An fMRI study. *Journal of Cognitive Neuroscience, 12*(2), 321–341.

Kuperberg, G. R., Sitnikova, T., Caplan, D., & Holcomb, P. J. (2003b). Electrophysiological distinctions in processing conceptual relationships within simple sentences. *Cognitive Brain Research, 17*(1), 117–129.

Kuperberg, G. R., Sitnikova, T., & Lakshmanan, B. M. (2008). Neuroanatomical distinctions within the semantic system during sentence comprehension: Evidence from functional magnetic resonance imaging. *Neuroimage, 40*(1), 367.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event related brain potential (ERP). *Annual Review of Psychology, 62*, 621.

Lifshitz Ben Basat, A., Gvion, A., Vatine, J. J., & Mashal, N. (2016). Transcranial direct current stimulation to improve naming abilities of persons with chronic aphasia: A preliminary study using individualized based protocol. *Journal of Neurolinguistics, 38*, 1–13.

Linzen, T. (2009). *Corpus of blog postings collected from the Israblog website (in manuscript)*. Tel Aviv University.

Marslen-Wilson, W., Brown, C. M., & Tyler, L. K. (1988). Lexical representations in spoken language comprehension. *Language and Cognitive Processes, 3*(1), 1–16.

Menenti, L., Petersson, K. M., Scheeringa, R., & Hagoort, P. (2009). When elephants fly: Differential sensitivity of right and left inferior frontal gyri to discourse and world knowledge. *Journal of Cognitive Neuroscience, 21*(12), 2358–2368.

Metzuyanim-Gorlick, S., & Mashal, N. (2016). The effects of transcranial direct current stimulation over the dorsolateral prefrontal cortex on cognitive inhibition. *Experimental Brain Research, 234*(6), 1537–1544.

Mordillo-Mateos, L., Turpin-Fenoll, L., Millán-Pascual, J., Núñez-Pérez, N., Panyavin, I., Gómez-Argüelles, J. M., … Oliviero, A. (2012). Effects of simultaneous bilateral tDCS of the human motor cortex. *Brain Stimulation, 5*(3), 214–222.

Ni, W., Constable, R. T., Mencl, W. E., Pugh, K. R., Fulbright, R. K., Shaywitz, S. E., Shaywitz, B. A., Gore, J. C., & Shankweiler, D. (2000). An event-related neuroimaging study distinguishing form and content in sentence processing. *Journal of Cognitive Neuroscience, 12*, 120–133.

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., … Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation, 1*(3), 206–223.

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *Journal of Physiology, 527*(3), 633–639.

Paczynski, M., & Kuperberg, G. R. (2012). Multiple influences of semantic memory on sentence processing: Distinct effects of semantic relatedness on violations of real-world event/state knowledge and animacy selection restrictions. *Journal of Memory and Language, 67*(4), 426–448.

Rayner, K., Warren, T., Juhasz, B. J., & Liversedge, S. P. (2004). The effect of plausibility on eye movements in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*(6), 1290.

Sehm, B., Kipping, J., Schafer, A., Villringer, A., & Ragert, P. (2013). A comparison between uni- and bilateral tDCS effects on functional connectivity of the human motor cortex. *Frontiers in Human Neuroscience, 7*, 183. http://dx.doi.org/10.3389/fnhum.2013.00183.

Sparing, R., Dafotakis, M., Meister, I. G., Thirugnanasambandam, N., & Fink, G. R. (2008). Enhancing language performance with non-invasive brain stimulation: A transcranial direct current stimulation study in healthy humans. *Neuropsychologia, 46*(1), 261–268.

Tesink, C. M., Buitelaar, J. K., Petersson, K. M., van der Gaag, R. J., Teunisse, J. P., & Hagoort, P. (2011). Neural correlates of language comprehension in autism spectrum disorders: When language conflicts with world knowledge. *Neuropsychologia, 49*(5), 1095–1104.

Van Berkum, J. J., Van den Brink, D., Tesink, C. M., Kos, M., & Hagoort, P. (2008). The neural integration of speaker and message. *Journal of Cognitive Neuroscience, 20*(4), 580–591.

Vines, B. W., Cerruti, C., & Schlaug, G. (2008). Dual-hemisphere tDCS facilitates greater improvements for healthy subjects' non-dominant hand compared to uni-hemisphere stimulation. *BMC Neuroscience, 9*(1), 103.

Warren, T., & McConnell, K. (2007). Investigating effects of selectional restriction violations and plausibility violation severity on eye-movements in reading. *Psychonomic Bulletin & Review, 14*(4), 770–775.

Weltman, K., & Lavidor, M. (2013). Modulating lexical and semantic processing by transcranial direct current stimulation. *Experimental Brain Research, 226*(1), 121–135.

Ye, Z., & Zhou, X. (2009). Conflict control during sentence comprehension: fMRI evidence. *Neuroimage, 48*(1), 280–290.