Journal of Cognitive Psychology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/pecp21

Can brain stimulation improve semantic joke comprehension?

Bat-el Yankovitz & Nira Mashal

JOURNAL OF COGNITIVE PSYCHOLOGY
2020, VOL. 32, NO. 4, 357–368
https://doi.org/10.1080/20445911.2020.1756832

Routledge
Taylor & Francis Group

Check for updates

Can brain stimulation improve semantic joke comprehension?

Bat-el Yankovitz[a] and 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

ABSTRACT
Semantic humour involves a deviation from lexico-semantic rules that introduces ambiguity into interpretation of a situation. The left Inferior Frontal Gyrus (IFG) has been implicated in humour processing (e.g. semantic puns, ambiguity resolution). The present study aimed to examine whether transcranial direct current stimulation (tDCS) over the left IFG would enhance semantic ambiguity resolution. In two sessions, fifteen participants aged 20–35 years received either offline anodal tDCS or sham stimulation for 20 min, after which they read semantically ambiguous humorous sentences, literal (non-ambiguous) sentences, and meaningless sentences, and then performed a semantic judgment task relating to each sentence's final word. Results showed that ambiguity resolution requires longer processing than literality. However, left IFG stimulation was ineffective in increasing ambiguity resolution. Researchers should target different brain areas in both hemispheres to further explore humour comprehension.

ARTICLE HISTORY
Received 18 September 2019
Accepted 11 April 2020

KEYWORDS
Humor; tDCS; left IFG; semantic ambiguity resolution

Introduction

Humour is a universal component of human experience and occurs in all cultures. The mental processing of humour refers to the comprehension of the incongruity of a joke. Incongruity occurs when the punchline is inconsistent with the sentence set-up. After resolving the incongruity, one can experience the pleasure of the joke (Scheel & Gockel, 2017). Jokes can be categorised into puns and semantic jokes. In order to understand semantic jokes it is necessary to resolve semantic incongruences between the sentence setup and the punchline (e.g. "Where's the place with the cheapest rent? … A prison."; Example adopted from Ku et al., 2020). A pun is defined as a type of a verbal joke that evokes a second meaning based on an ambiguous word: a homophone (i.e. a word with a different meaning that sounds the same). Thus, puns provide contextual support for two different meanings of an ambiguous word, eliciting two incompatible interpretations of the joke (e.g. "Why don't cannibals eat clowns? Because they taste funny."). The present study focuses on pun comprehension that requires the disambiguation of a final word that possesses multiple meanings, in which one particular meaning has to be chosen (Bekinschtein et al., 2011; Zempleni et al., 2007).

One of the traditional theories of humour processing is the two-stage model suggested by Suls* [1](1972). According to Suls, the perceiver first encounters an incongruity between their expectation and the ending of the joke (the punchline). In the second stage, the perceiver reconciles the incongruous part of the joke. Whereas Suls views humour comprehension as a type of cognitive problem-solving task, Wyer and Collins (1992) suggested a different two-stage model that includes a cognitive stage (comprehension) and a cognitive-emotional stage (elaboration). This model posits that humour *comprehension* involves being surprised by an unexpected ending and resolving of the incongruity by reinterpreting the situation. Humour *elaboration* consists of inferring conclusions from the newly interpreted situation and understanding that one can look at the same situation

CONTACT Nira Mashal mashaln@mail.biu.ac.il
Supplemental data for this article can be accessed https://doi.org/10.1080/20445911.2020.1756832
[1]Please note: Suls (1972) is widely cited for his theory and one of the jokes he gives as an example is also highly cited (Suls, 1972, p. 8). The joke goes as follows, "One prostitute said to another, 'Can you lend me ten dollars until I get back on my back?'". This joke is inappropriate and chauvinist, and not in line with what is appropriate to our day and age.

differently, which elicits the unconscious or conscious feeling of amusement. Both models suggest that humour comprehension is processed sequentially over multiple cognitive steps (Ku et al., 2020). Scholars agree that humour processing can thus be divided into three sub-stages: incongruity detection, incongruity resolution, and elaboration (Chan et al., 2013; Feng et al., 2014).

Different theories explaining humour comprehension highlight the importance of mentalizing ability or "theory of mind" (ToM) in the appreciation of humour. For example, the mind-reading hypothesis of humour (Howe, 2002) differentiates laughter from humour. Laughter is posited to come from a relief of tension, whereas humour involves an observer reading the mind of the "target" of the joke and observing that the target resolves "the collision between old perception and new reality" (Howe, 2002). Jung (2003) proposed the "inner eye" theory of laughter which presupposes understanding the desires or beliefs of both the joke-teller and the characters in the joke. These theories argue that different types of verbal jokes induce different degrees of mentalization processes.

Several neuroimaging studies tested the neural substrates of humour comprehension. For instance, Zempleni et al. (2007) examined semantic ambiguity processing using functional magnetic resonance imaging (fMRI). Participants read sentences whose final word was a homophone and were instructed to indicate whether the final word created a meaningful sentence. The results indicate the involvement of a bilaterally distributed network including the inferior frontal gyrus (IFG) and inferior/middle temporal gyri. Moreover, in a study that examined the understanding of jokes, a comparison was made between jokes that rely on semantics and jokes in which the punchline is phonological. Participants were asked to answer whether each of a series of semantic and phonological jokes was funny and to rate each joke's degree of amusement. Results showed that the left IFG was activated during the phonological jokes (Goel & Dolan, 2001). Further studies found left IFG activation during processing of nonverbal cartoons (Mobbs et al., 2003; Samson et al., 2008). Thus, evidence from neuroimaging studies appears to show left IFG involvement in understanding humour.

Previous fMRI studies of humour processing often compared a funny condition with an unfunny condition, but often did not attempt to isolate the theorised components, or phases, *within* humour processing itself, such as the comprehension and the elaboration stages suggested by Wyer and Collins (1992). However, Chan et al. (2012) conducted an fMRI study designed to distinguish the neural substrates involved in the comprehension and the elaboration stages of humour processing. The study included, in addition to unfunny condition, a "garden path" condition to elicit incongruity resolution processes associated with humour comprehension but not with elaboration. The results indicated that the bilateral IFG and left superior frontal gyrus may be associated with humour comprehension, whereas the left ventromedial prefrontal cortex and subcortical structures (the bilateral amygdalae and bilateral parahippocampal gyri) are activated during the feeling of amusement during the elaboration process. An ERP study that tested humour using verbal jokes reported different findings. The amplitude of the N400 priming effect (which reflects the difficulty of semantic integration) (Gold et al., 2010) was larger with presentation to the left visual field, suggesting joke-relevant information was more active in the right hemisphere (Coulson & Wu, 2005; see also Bartolo et al., 2006 for right IFG involvement in processing semantic aspects of incongruity resolution). Thus, neuroimaging studies show possible bilateral IFG involvement in the understanding of humour.

In the last decades, transcranial direct current stimulation (tDCS) has emerged as a research tool. TDCS induces short-term changes in cortical excitability by applying weak electrical currents over targeted brain regions. 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, whilst cathodal stimulation appears to have the opposite effect. TDCS may be used to improve cognitive abilities in healthy and clinical populations (Brunoni & Vanderhasselt, 2014; Metzuyanim-Gorelick & Mashal, 2016; Nitsche & Paulus, 2000). For instance, a recent study examined whether stimulation can improve understanding when a semantic or pragmatic violation is presented (e.g. *At dinner my uncle drunk a rock, At dinner my uncle drunk gasoline*; respectively). Results of bilateral stimulation applied over the superior temporal gyrus (STG) area (anode electrode over left STG, cathode electrode over right STG), showed faster response times for the pragmatic violations than for the semantic violations. Thus, a short STG stimulation may improve pragmatic processing (Osovlanski & Mashal, 2017).

Only a few studies, however, tested the effects of tDCS on humour comprehension. Manfredi et al. (2017), for example, presented participants with slapstick humour scenes after applying bilateral stimulation (anodal electrode over the right STG and cathodal over the left STG, and vice versa). The results showed that, in both stimulation conditions, tDCS over the STG improved humour comprehension during observation of unfortunate situations (Manfredi et al., 2017). In contrast, in a study that showed participants humorous videos, the results indicated decreased humour ratings during anodal stimulation over the left temporoparietal junction (Slaby et al., 2015). A recent study (Manfredi et al., 2019) examined whether anodal tDCS over medial prefrontal cortex (MPFC), right temporoparietal junction (rTPJ), and occipital cortex would facilitate the comprehension of comic strips that require ToM abilities in order to be properly understood. This study was particularly interested whether brain networks associated with ToM-related humour processing are selectively active during the ToM information processing or if they are more generally involved in the resolution of a semantic incongruity. Thus, their control conditions included non-ToM humorous strips (Humorous non-ToM), non-humorous strips that were semantically coherent but not funny (Congruent), and non-humorous strips that were semantically incoherent (Incongruent). The overall results did not show significant differences between tDCS conditions on response times. However, humorous ToM strips were rated as more humorous when stimulation was applied over the MPFC stimulation (but not over rTPJ) as compared to sham stimulation. The results indicated that MPFC stimulation improved the ability to identify a non-humorous incongruent element and to recognise the humorous element of the scene. Thus, the findings regarding the effect of tDCS on humour processing are inconsistent and use different types of humour stimuli, tasks, and sites of stimulation. Further studies targeting additional brain regions are needed to determine whether and how tDCS can affect humour comprehension.

The aim of the present study was twofold: (1) to examine the processing of humorous sentences containing semantic ambiguity compared to literal (non-ambiguous) sentences; (2) to test whether anodal tDCS over the left IFG would enhance semantic ambiguity resolution. Based on the framework established by the comprehension-elaboration theory of humour processing (Wyer & Collins, 1992), we expected faster response times for processing the literal sentences than the humorous ones, since the semantic ambiguities presented in the humorous sentences elicit additional processes such as incongruity detection, incongruity resolution, and elaboration (Chan et al., 2013; Feng et al., 2014). We also hypothesised that, as IFG has been implicated in the processing of humour (Chan et al., 2013) and, in particular, in semantic puns and ambiguity resolution (Samson et al., 2008), anodal (excitatory) stimulation of this region would improve ambiguous joke comprehension via facilitating incongruity detection and incongruity resolution.

Materials and Methods

Participants

Fifteen volunteers (ten females) who were right-handed (according to self-report) native Hebrew speakers participated in the study. The participants' age range was 20–34 years ($M = 29.2$, $SD = 3.37$). Participants had no history of learning disorders, psychiatric disturbances, neurological disease, head trauma, or pregnancy (for women) according to self-report. All participants received active brain stimulation and sham stimulation randomly within the course of one week and were blinded to the type of tDCS delivered at each session. All participants completed the Empathy Quotient (EQ) (Baron-Cohen & Wheelwright, 2004) that is designed to test the ability of expressing empathy and understanding other's intentions. The questionnaire contains 40 empathy items and 20 filler/control items. On each empathy item a person can score 2, 1, or 0, so the EQ has a maximum score of 80 and a minimum of zero. The mean empathy score of the participants was 48 (score range = 30–76; $SD =$ 13.67). No significant correlations were found between the EQ scores and response times on the literal and the humorous sentences in both the active and the sham stimulation.

Task and stimuli

The stimulus pool consisted of 180 Hebrew sentences divided into three types: 60 humorous (semantically ambiguous sentences), 60 literal (non-ambiguous) sentences, and 60 meaningless sentences. The final words of the humorous and the literal sentences were ambiguous homophones. For each final word, two sentences were constructed: a literal, non-ambiguous sentence and a humorous ambiguous sentence. The final word of the humorous sentence (e.g. cold) was consistent with the sentence meaning (e.g. *The beggar asked money from the ice cream seller, but the seller's response was cold.*). However, the final word was semantically related to two different nouns within the sentence (both "ice cream" and "response"). This sentence was paired with a literal sentence ending with the same final word (e.g. *Ron asked his mother for ice cream and she said the ice cream was too cold.)*. An additional set of 60 meaningless sentences ending with an unrelated final word were also constructed (e.g. "*Sarah had a big test yesterday. She studied and during the test she had a lake."*).

Two lists were presented to the participants, each list containing 30 literal, 30 humorous, and 30 meaningless sentences (with the literal sentences in one list sharing the same ambiguous final word as the humorous sentences in the second list). The participants performed a semantic judgment task on the final word of each sentence.

Stimulus Construction

Several pre-tests were performed in order to validate the sentences and to verify whether the two commonly acceptable meanings of the final words were understood.

Pre-test for meaning

Each sentence evoked a literal association in addition to a humorous association, so participants were presented with two meanings to examine whether the last word was strongly associated with both meanings. For example: "*The beggar asked money from the ice cream seller, and the seller's response was cold.*" Participants were presented with two sentences: "The ice cream was cold" and "The response was cold" and were asked to rate the degree of semantic relatedness between the final word (*cold*) and each sentence's meaning using a scale ranging from 1–7 (1 = not related at all, 7 = highly related). Ten participants (age range: 20–35 years; $M = 26.26$; $SD = 4.35$) participated in the pretest (2 men). These participants did not take part in the second pre-test or the live experiment. The pre-test stimulus pool consisted of 65 sentences. As a result of the pre-testing, 62 sentences remained. Items with an average rating greater than 4 were selected for the experiment and two lists were constructed: list 1 (humorous meaning: $M = 5.72$, $SD = 0.76$, literal meaning: $M = 6.01$, $SD = 0.69$) and list 2 (humorous meaning: $M = 5.65$, $SD = 0.93$, literal meaning: $M = 6.33$, $SD = 0.49$).

Pre-test for Surprise/Enjoyment

The second pre-test was aimed at examining to what extent the final word of each the sentence was surprising and enjoyable. Thirty participants (10 men) aged 18–34 years ($M = 27.4$, $SD = 5.42$) participated in this pre-test. These participants did not take part in the first pre-test or in the live experiment. They were asked to rate how much the last word in the sentence was surprising on a scale of 1–7 (1 = not at all surprising, 7 = very surprising). They were also asked to indicate to what extent the sentences were enjoyable for them on a scale ranging from 1–7 (1 = not enjoyable at all, 7 = very enjoyable). Items rated above 4 on each scale were selected for the humour condition. The mean rate of the sentences on the "surprising" scale was 5.08 ($SD = 0.47$), and on the "enjoyable" scale was 5.01 ($SD = 0.59$). Items rated below 4 were selected for the literal sentences. After this second pre-test, 60 items were left in each condition (humorous, literal).

Pre-test for syntactic category, word length, word frequency

Finally, the aim of this third kind pre-testing was to counterbalance the lists and the conditions according to the final word syntactic category, word length, and word frequency. The final word syntactic category included five types of words: adjectives, nouns, verbs, words that are both nouns and adjectives, and words that are both verbs and adjectives. The word length and word frequency (based on Linzen, 2009) are summarised in Table 1.

In order to verify there were no significant differences between the three types of words (humorous, literal, meaningless) in word length and frequency, two analyses were conducted, one for the word length and one for the word frequency. Thus, two repeated measures ANOVAs with word type (humorous, literal, meaningless) as the within-subject factor and list (list 1, list 2) as the between-subjects factor were conducted.

Table 1. Final word length and frequency* (Mean and SD).

	Length		Frequency	
	List 1	List2	List 1	List 2
Humorous	4.50 (1.54)	4.47 (1.25)	6753.43 (14873.99)	6235.60 (14607.78)
Literal	4.47 (1.25)	4.47 (1.50)	6235.60 (14607.78)	6753.43 (14873.99)
Meaningless	4.50 (1.38)	4.40 (1.42)	6367.77 (16139.71)	6680.33 (16187.18)

*Frequency of occurrence per million Hebrew words.

Word length

The main effect of word type (humorous, literal, meaningless) on word length was non-significant $F[2, 2] = 0.20$, $p = .980$, $\eta_p^2 = .00$. The main effect of list (list 1, list 2) on word length was also non-significant $F[1, 1] = 0.05$, $p = .809$, $\eta_p^2 = .00$. The interaction was non-significant $F[2, 2] = 0.18$, $p = .982$, $\eta_p^2 = .00$. Thus, word length was balanced across the conditions and the two lists.

Word frequency

The main effect of word type (humorous, literal, meaningless) on word frequency was non-significant $F[1, 1]$ =.07, $p = 0.784$, $\eta_p^2 = .00$. The main effect of list (list 1, list 2) on word frequency was non-significant as well, $F[2, 2] = 0.00$, $p = 1.000$, $\eta_p^2 = .00$. The interaction was also non-significant $F[1, 1] = 0.07$, $p = .785$, $\eta_p^2 = .00$. Thus, the final word frequency was counterbalanced across the three experimental conditions.

Pre-test for response times and accuracy rates

In the last pre-test, the goal was to validate the sentences in terms of response times (RTs) and accuracy rates using a computerised task. We expected longer RTs for the humorous sentences compared to the literal ones. The sentences were divided into two lists, each list including 90 sentences (30 of each type: humorous, literal, meaningless). Twenty right-handed participants (10 women) whose ages ranged 18–35 years old (*M* = 25.7, *SD* = 5.24(participated in the test. Half of the participants were presented with list 1 in the first session followed by list 2 in the second session (and the other half vice versa).

Participants read three types of sentences: humorous (semantically ambiguous sentences), literal (non-ambiguous), and meaningless. The participants were instructed to decide whether the final word made a logical ending to the sentence. Participants performed a semantic judgment task on the final word by clicking "yes" (by pressing the N key) with their right finger for a word that related to (matched the logic of) the sentence, or "no" (by pressing the B key) for a word that formed a meaningless sentence. The participants were instructed to respond as rapidly and accurately as possible.

The experiment started with a practice session using six sentences that did not appear in the experiment. The sentences were presented on a screen for 2,200–3500 ms (depending on sentence length); the whole sentence, without the final word, was first shown on the screen, followed by the final, target word that was displayed in isolation for 500 ms in the centre of the screen. The stimuli were displayed via SuperLab version 5.0 software installed on a laptop (Cedrus Corp, San Pedro, CA). Response times and accuracy rates for each condition are presented in Figure 1.

Pre-Testing reaction time analysis

After omitting outliers (responses ± 2 *SD* from the mean taken across all trials of each condition), we computed mean reaction times (RTs) for correct responses for each participant in each condition. A two-way 3 X2 repeated measures ANOVA with sentence type (humorous, literal, meaningless) as the within-subjects factor and list (list 1, list 2) as the between-subjects factor was computed for reaction time. The main effect of sentence type was significant $F[2, 2] = 18.93$, $p < .001$, $\eta_p^2 = .51$. Bonferroni adjusted t-testing revealed that, as expected, the overall response times for the literal sentences were faster than the humorous ones, $p < 0.001$. No significant difference was found between the humorous and meaningless sentences, $p = 1.000$. In addition, literal sentences were processed faster than meaningless sentences, $p < 0.001$. The main effect of list was non-significant $F[1, 1] = 0.01$, $p = .917$, $\eta_p^2 = .00$. Thus, there was no difference between the two lists on response times. The Sentence Type X List interaction was also non-significant $F[2, 2] = 0.88$, $p = .424$, $\eta_p^2 = .04$.

Pre-Testing accuracy analysis

A two-way3 X2 repeated measures ANOVA with sentence type (humorous, literal, meaningless) as the

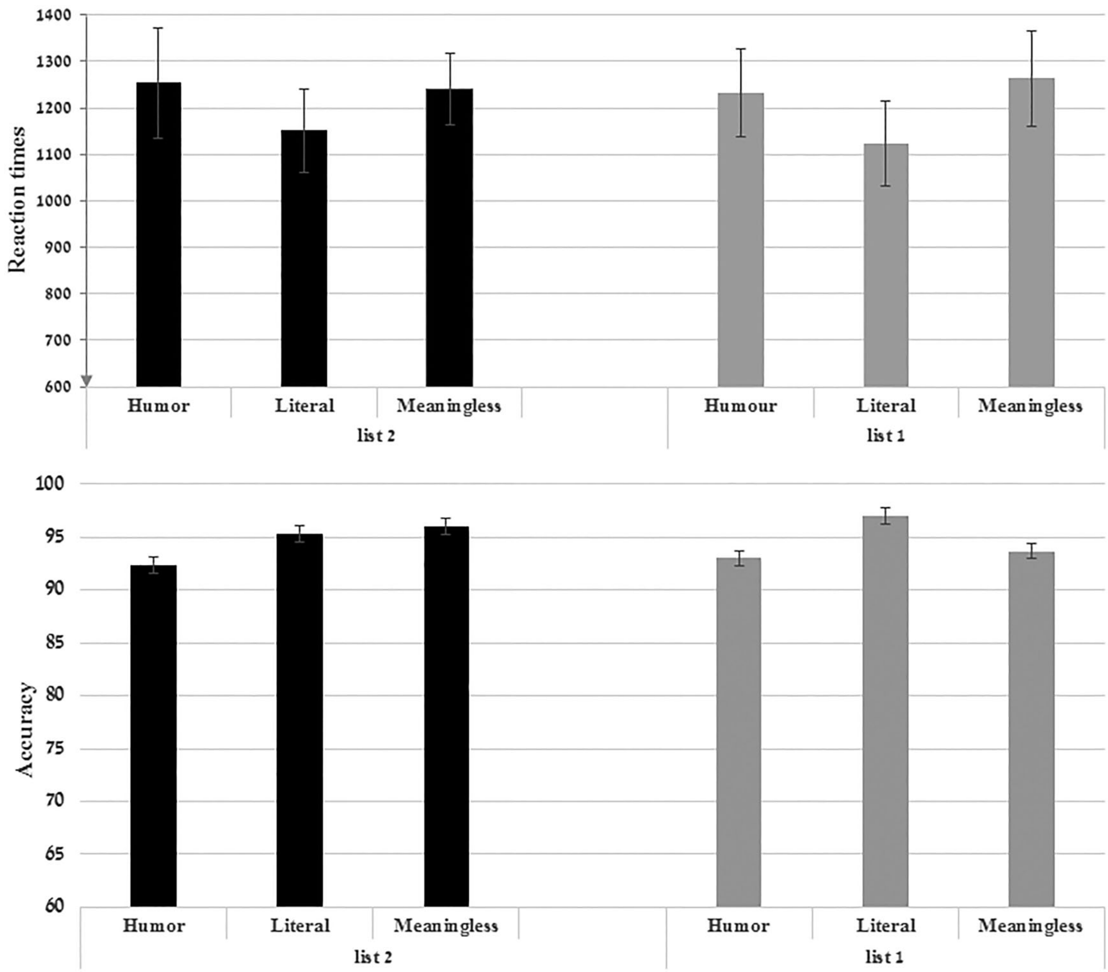

Figure 1. Mean RTs and accuracy rate and SDs (pre-test).

within-subjects factor and list (list 1, list 2) as the between-subjects factor was computed for accuracy rate. The main effect of sentence type although was non-significant, F[2, 2] = 2.88, $p = .069$, $\eta_p^2 = 0.13$, indicating a trend towards humorous sentences producing lower accuracy than literal sentences. Also, the main effect of list was non-significant as well, F[1, 1] = 0.00, $p = 1.000$, $\eta_p^2 = .00$ and the interaction was also non-significant F[2, 2] = 1.00, $p = .378$, $\eta_p^2 = .05$.

In summary, these pre-testing results show faster responses to the literal than the humorous sentences, suggesting that, as expected, ambiguity resolution takes longer to process than literality.

Brain stimulation experiment

The aim of the experiment was to examine whether tDCS over the left Inferior Frontal Gyrus (IFG) would enhance semantic ambiguity resolution.

tDCS Protocol

tDCS was administered using a battery-driven, constant current stimulator (neuroConn DC stimulator plus, Incl GmbH), and a pair of conductive rubber electrodes (5 cm×5, 25 cm2) covered in normal saline-soaked, synthetic sponges restrained by a headband (Loo et al., 2011). Each side of the sponges was soaked with about 6 mL of saline solution (a total of 12 mL per sponge) of 0.09% NaCl concentration. A syringe was used to add more solution if needed. Fluid leaking was avoided by placing a towel across the participant.

Unilateral montage was conducted to increase the activation of the left IFG function. To stimulate the left IFG, the anodal (excitatory) electrode was placed above the left IFG and the cathodal (suppression) electrode was placed on the right-side forehead. Electrode placement was done in accordance with the 10–20 international system for EEG electrode placement using universal electrode caps for standardised head sizes (see Seibt et al., 2015) with the longer side of the electrode positioned vertically. Each stimulation was applied for 20 min at 1.5-mA intensity. For the sham condition, the stimulation ceased after 30 s to allow for perception of an "itchy" sensation that accompanies the beginning of stimulation, in order to achieve a blinded effect, but provide an insufficient amount stimulation to produce an effect.

Procedure

The study plan was approved by the Ethics Committee of the School of Education at Bar Ilan University. Informed consent was obtained from all individual participants included in the study.

At the start of the experiment, the participants completed the Stanford questionnaire (Hoddes et al., 1972). This scale serves as a subject self-assessment tool for one's level of alertness. The questionnaire includes eight statements describing a level of sleepiness/alertness from (1) wide awake to (8) asleep. The participant was asked to choose the number of the statement that best describes the participant's level of alertness at the moment of participation in the study. All participants chose level 1 (wide awake) and reported that they were very alert and ready to do the experiment.

Each participant underwent two sessions with one week in between the sessions. Half of the participants participated in the active (anodal) stimulation in the first session followed by sham stimulation in the second session, and half of the participants vice versa. Half of the participants were presented in the first session with list 1 followed by list 2 in the second session, and half of the participants vice versa. During the stimulation, participants were quietly resting. At the end of each stimulation, they completed the computerised experiment. The length of each session, including stimulation, took 45 min; subjects were given a break at the session's mid-point.

In the sham stimulation session, participants followed the same procedure via the computerised task. As in the active stimulation session, the length of the session took 45 min, and participants were given a break in the middle of the experiment. The stimuli were displayed via SuperLab version 5.0 software installed on a laptop (Cedrus Corp, San Pedro, CA). The experiment's stimulus presentation and task were identical to the pre-test versions.

Results

Analyses were performed on the inverse efficiency scores. After removing outliers (responses ± 2 *SD* from the mean taken across all trials of each condition), we computed mean reaction times (RTs) for correct responses and divided them by the percentages of correct responses (inverse efficiency scores) for each participant in each condition. We used the inverse efficiency score to quantify both aspects of performance (i.e. RT and accuracy) in a single measure (Bruyer & Brysbaert, 2011). See Figure 2 for the efficiency scores. (See supplementary materials for RTs, accuracy and inverse efficiency scores).

All participants tolerated the stimulation well, did not report any sensation of pain or uncomfortable feelings during the stimulation sessions, and no side effects were observed throughout the experiment.

A four-way 3X2X2X2 repeated measures ANOVA was performed on the efficiency scores with sentence type (humour, literal, meaningless) and stimulation type (anodal, sham) as the within-subjects factors and list (list 1, list 2) and order (anodal first, sham first) as the between-subjects factors. All interactions with order and list were non-significant, including the four-way interaction, F [2, 22] = 1.88, $p = .176$, $\eta_p^2 = .14$, and therefore list and order were collapsed within the data.

A two-way 3X2 ANOVA with sentence type (humorous, literal, meaningless) and stimulation type (anodal, sham) was conducted. This analysis revealed a non-significant main effect of stimulation type, F [1, 14] = 2.08, $p = .171$, $\eta_p^2 = 0.12$. However, the main effect of sentence type was significant, F [2, 28] = 8.06, $p = .002$, $\eta_p^2 = 0.36$. Pairwise comparisons revealed that responses were more efficient for literal than humorous sentences, $p = .009$, but no significant difference was found between the humorous and meaningless sentences, $p = 0.850$. In addition, a significant difference between the literal and meaningless sentences was revealed, $p = .003$, in that the literal sentences were processed more efficiently than both the humorous sentences and the meaningless sentences. The two-way interaction of sentence type and stimulation type was non-significant, F [2, 28] = 0.91, $p = .413$, $\eta_p^2 = 0.06$. In summary, no effect of active stimulation on efficiency scores was found, compared to sham stimulation (see Figure 2).

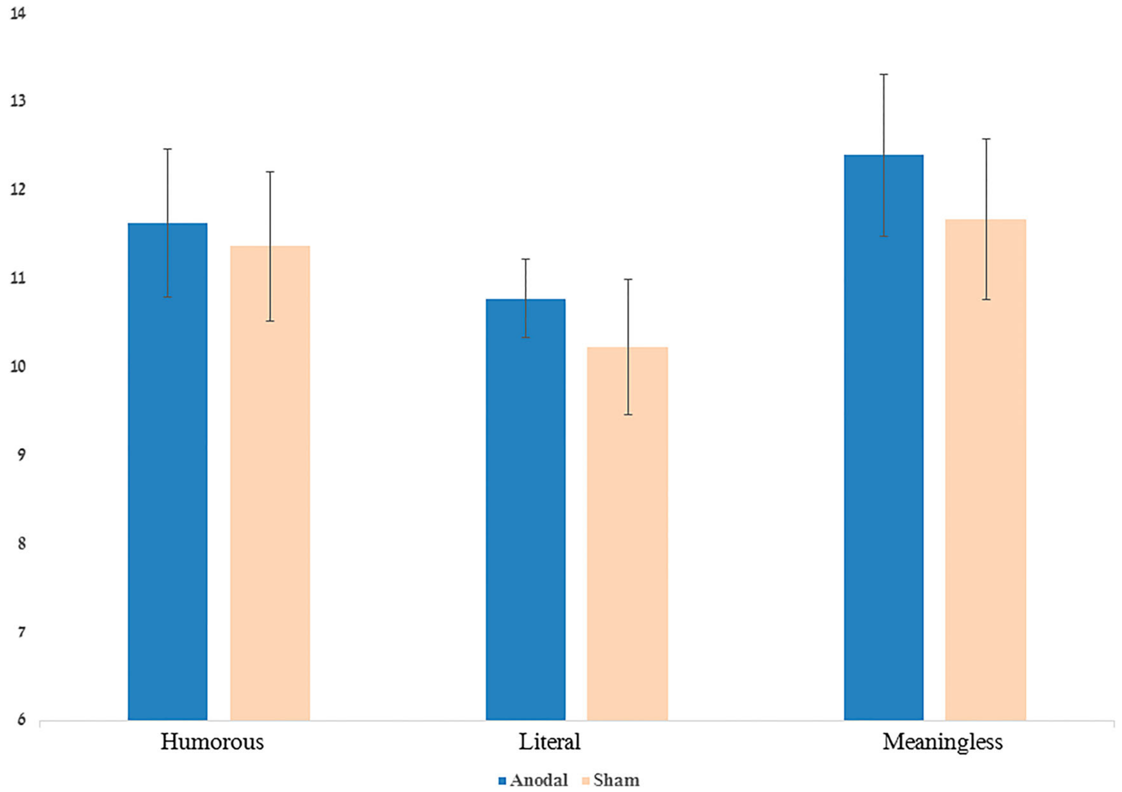

Figure 2. Mean efficiency scores and SDs by sentence type and stimulation type.

RT analysis

A four-way 3X2X2X2 repeated measures ANOVA was performed on the reaction times scores with sentence type (humour, literal, meaningless) and stimulation type (anodal, sham) as the within-subjects factors and list (list 1, list 2) and order (anodal first, sham first) as the between-subjects factors (see Table 2). All interactions with order and list were non-significant, including the four-way interaction, F [2, 22] = 0.95, $p = .402$, $\eta_p^2 = .08$, and therefore list and order were collapsed within the data.

A two-way 3X2 ANOVA with sentence type (humorous, literal, meaningless) and stimulation type (anodal, sham) was conducted. This analysis revealed a non-significant main effect of stimulation type, F [1, 14] = 2.00, $p = .179$, $\eta_p^2 = 0.12$. However, the main effect of sentence type was significant, F [2, 14] = 19.18, $p < .001$, $\eta_p^2 = 0.57$. Pairwise comparisons revealed that responses were faster for literal than humorous sentences, $p = .001$, and for humorous than meaningless sentences, $p = 0.016$. In addition, a significant difference between the literal and meaningless sentences was revealed, $p < .001$, in that the literal sentences were processed faster than both the humorous sentences and the meaningless sentences. The two-way interaction of sentence type and stimulation type was non-significant, F [2, 28] = 0.22, $p = .799$, $\eta_p^2 = 0.01$. Thus, similar results were obtained in the RT and inverse efficiency score analyses (except the humorous sentences that showed faster response times than the meaningless sentences in the RT analysis but not in the efficiency score analysis). As can be seen in

Table 2. Mean RTs and accuracy rate (and SDs) by sentence type (humour, literal, meaningless) and stimulation type (active, sham).

	Reaction Times List 1	Reaction Times List 2	Accuracy List 1	Accuracy List 2
Humour active	1135.51 (152.05)	1006.37 (172.37)	91.66 (6.66)	93.80 (5.58)
Humour sham	1014. 58 (72.46)	1034.32 (122.39)	91.25 (7.11)	91.90 (4.65)
Literal active	1039.79 (138.89)	984.84 (140.13)	92.91 (6.28)	95.71 (3.70)
Literal sham	966.74 (73.62)	992.78 (103.83)	96.66 (3.98)	94.76 (5.03)
Meaningless active	1170.88 (153.48)	1108.73 (153.94)	94.16 (6.10)	90.47 (9.89)
Meaningless sham	1104.34 (115.60)	1099.22 (123.99)	96.66 (6.42)	92.85 (6.50)

Table 2, the accuracy rate was at ceiling and therefore was not analysed.

Discussion

The present study demonstrated that non-ambiguous literal sentences are processed more efficiently than ambiguous, enjoyably humorous sentences. To the best of our knowledge, this is the first study that shows this effect. Another finding that emerged from the current study is the lack of effect of tDCS over the left IFG on increasing semantic ambiguity resolution in humour comprehension.

The more efficient (and faster) processing of non-ambiguous sentences over ambiguous humorous sentences is consistent with the framework of comprehension-elaboration theory of humour processing (Wyer & Collins, 1992). Namely, an additional interpretation is elicited during the reading of an ambiguous sentence and selecting the correct interpretation results in less efficient processing than for literal sentences. Thus, because humour demands interpreting a scenario differently in order to resolve an incongruity, this processing takes more time compared to direct language (Chan et al., 2013). This finding is consistent with an ERP study which tested written humour compared to written literal statements. The results indicated that when jokes were shown to the right hemisphere, a larger N400 amplitude emerged compared to that elicited by statements with non-humorous endings. Thus, processing literal sentences is a less demanding task resulting in more efficient processing compared to humour (Coulson & Williams, 2005). Our findings also showed that although humorous sentences are processed as efficiently as meaningless sentences, the RT analysis indicated that humorous sentences are processed faster than the meaningless sentences. This finding may indicate that the process of understanding an ambiguous sentence ends on resolving the incongruity that emerges on encountering the sentence final word. However, when reading a meaningless sentence, the reader continues to search for a correct interpretation, a process that takes longer than resolving the incongruency. Thus, the time it takes to process literal, ambiguous (humorous) and meaningless sentence is performed gradually, with literal faster than ambiguous and ambiguous faster than meaningless sentence.

The current study also examined whether brain stimulation using tDCS over the IFG enhanced semantic ambiguity resolution in comprehension of puns. Contrary to our hypothesis, the results did not provide support for the IFG being causally involved in ambiguous humour processing. Humour processing, including pun processing, is a complex behavioural task: it relies on incongruity detection, incongruity resolution, and elaboration (Chan et al., 2013; Feng et al., 2014). It is possible that the tDCS effect might be too subtle to modulate such a complex process at the behavioural level. Alternatively, the lack of evidence of performance enhancement may be linked to the type of testing utilised in the current study: we used a semantic judgment task (deciding whether or not a sentence made sense). Other tDCS studies used different tasks, such as |Manfredi et al. (2017, 2019) who used a humour appreciation task ("Is it comic") and Slaby et al. (2015) who also used a humour appreciation task in which participants rated comedy clips. In contrast, the current study used a more cognitively demanding task that required participants not only to detect incongruity but also to resolve it (choosing the congruent meaning of the homophone). Our hypothesis was based on previous neuroimaging studies pointing to the involvement of the left IFG in ambiguity resolution (Mobbs et al., 2003; Moran et al., 2004; Samson et al., 2008). For instance, Moran et al. (2004) examined the brain response to viewing full-length episodes of television sitcoms "Seinfeld" or "The Simpsons," revealing increased activation in the left IFG and posterior temporal cortices. However, it is possible that their use of video clips, instead of the written material used in the current study, contributed to the apparently conflicting findings. In sum, the lack of confirmation of our second hypothesis is challenging to interpret, as it may be result of a few different factors, not the least of which is the difficulty of choosing a single cerebral region (one node of a brain network) and attempting to measure complex processes endorsed by this region after applying tDCS.

Indeed, emerging evidence suggests that a different cerebral region may be involved in humour processing. A recent stimulation study examined the effect of bilateral tDCS over the STG on the processing of humorous slapstick scenes depicting facial expressions (comic, affective non-comic, non-facial) (Manfredi et al., 2017). Results showed faster RTs in response to both the comic and non-facial stimuli conditions (following anodal-left/cathodal-right stimulation) as compared to sham stimulation, suggesting that the left STG might be involved in a general comprehension of complex social situations. Faster RTs were also observed following anodal-right/cathodal-left stimulation for comic stimuli only, suggesting that the right STG may be involved in the appreciation of the comic element in unfortunate situations. Future studies should test whether STG stimulation (combined with bilateral instead of unilateral stimulation) may also affect ambiguous humour sentence processing.

The current study has some limitations. The sample was small- only fifteen participants; future studies may wish to use a larger sample size. Moreover, as the results did not find evidence (even a non-significant trend) supporting the causal role of tDCS on humour processing, future studies may wish to target a different brain region (e.g. STG). In addition, this study employed offline tDCS, since participants received stimulation before the experimental task began. As it has been shown that "online" tDCS (i.e. during the task performance) is superior to "offline" tDCS for enhancing skill acquisition when combining anodal tDCS with cognitive training (Martin et al., 2014), it is possible that online tDCS may have stronger behavioural effects on humour processing. Indeed, a tDCS study that tested humour appreciation using online tDCS found reduced response times during humour appreciation performance compared to sham stimulation (Manfredi et al., 2017). Additionally, the stimulation of a "control" brain area not known to be involved in semantic ambiguity processing and humour processing, such as the occipital cortex (Manfredi et al., 2019) would enhance future research. Moreover, providing a computational simulation of the electrical field induced by tDCS would allow assessment of its strength and extent at each location on the cortical surface across subjects (e.g. Saturnino et al., 2019), enabling augmented interpretation of study results. Another limitation of the current study was testing only semantic ambiguity related humour; it is possible that humour based on phonology, and not semantic incongruity may be more receptive to brain stimulation (Goel & Dolan, 2001). In the work of Goel and Dolan (2001), the difference between jokes in which the punchline was semantic versus phonological in nature was examined; they found that semantic juxtaposition used a bilateral temporal lobe network, whereas phonological juxtaposition used a left hemisphere network centred around speech production regions. Accordingly, lateralisation considerations should be taken into account when stimulating target brain regions. It is possible that stimulation of areas in the right hemisphere may contribute to the processing of humour; the current study only stimulated the left hemisphere. Indeed, evidence from fMRI studies reveals brain activity in the right hemisphere whilst processing humour as well (Samson et al., 2009; Watson et al., 2006). Finally, although all participants reported having no psychiatric disorders, depression and anxiety should be assessed in order to exclude participants with high level of depression or anxiety, as this may be a confound with humour comprehension.

In sum, we found no evidence for an effect by tDCS over left IFG on ambiguous humour processing. Nevertheless, our results show that ambiguous, humorous sentences are processed less efficiently than literal sentences likely due to the resources required to process two initial interpretations (i.e. polysemy within a sentence distracts from its processing). Future brain stimulation studies are recommended to target different regions in both the left and right hemispheres to understand their impact on humour comprehension.

Acknowledgments

We would like to thank Shira Chana Bienstock for her thorough editorial review of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within its supplementary materials.

References

Baron-Cohen, S., & Wheelwright, S. (2004). The empathy quotient: An investigation of adults with asperger syndrome or high functioning autism, and normal Sex differences. *Journal of Autism and Developmental Disorders*, *34*(2), 163–175. https://doi.org/10.1023/B:JADD.0000022607.19833.00

Bartolo, A., Benuzzi, F., Nocetti, L., Baraldi, P., & Nichelli, P. (2006). Humor comprehension and appreciation: An FMRI study. *Journal of Cognitive Neuroscience*, *18*(11), 1789–1798. https://doi.org/10.1162/jocn.2006.18.11.1789

Bekinschtein, T. A., Davis, M. H., Rodd, J. M., & Owen, A. M. (2011). Why clowns taste funny: The relationship between humor and semantic ambiguity. *Journal of Neuroscience*, *31*(26), 9665–9671. https://doi.org/10.1523/JNEUROSCI.5058-10.2011

Brunoni, A. R., & Vanderhasselt, M. A. (2014). Working memory improvement with non-invasive brain stimulation of the dorsolateral prefrontal cortex: A systematic review and meta-analysis. *Brain and Cognition*, *86*, 1–9. https://doi.org/10.1016/j.bandc.2014.01.008

Bruyer, R., & Brysbaert, M. (2011). Combining speed and accuracy in cognitive psychology: Is the inverse efficiency score (IES) a better dependent variable than the mean reaction time (RT) and the percentage of errors (PE)? *Psychologica Belgica*, *51*(1), 5–13. https://doi.org/10.5334/pb-51-1-5

Chan, Y. C., Chou, T. L., Chen, H. C., & Liang, K. C. (2012). Segregating the comprehension and elaboration processing of verbal jokes: An fMRI study. *NeuroImage*, *61*(4), 899–906. https://doi.org/10.1016/j.neuroimage.2012.03.052

Chan, Y. C., Chou, T. L., Chen, H. C., Yeh, Y. C., Lavallee, J. P., Liang, K. C., & Chang, K. E. (2013). Towards a neural circuit model of verbal humor processing: An fMRI study of the neural substrates of incongruity detection and resolution. *Neuroimage*, *66*, 169–176. https://doi.org/10.1016/j.neuroimage.2012.10.019

Coulson, S., & Williams, R. F. (2005). Hemispheric asymmetries and joke comprehension. *Neuropsychologia*, *43*(1), 128–141. https://doi.org/10.1016/j.neuropsychologia.2004.03.015

Coulson, S., & Wu, Y. C. (2005). Right hemisphere activation of joke-related information: An event-related brain potential study. *Journal of Cognitive Neuroscience*, *17*(3), 494–506. https://doi.org/10.1162/0898929053279568

Feng, Y. J., Chan, Y. C., & Chen, H. C. (2014). Specialization of neural mechanisms underlying the three-stage model in humor processing: An ERP study. *Journal of Neurolinguistics*, *32*, 59–70. https://doi.org/10.1016/j.jneuroling.2014.08.007

Goel, V., & Dolan, R. J. (2001). The functional anatomy of humor: Segregating cognitive and affective components. *Nature Neuroscience*, *4*(3), 237–238. https://doi.org/10.1038/85076

Gold, R., Faust, M., & Goldstein, A. (2010). Semantic integration during metaphor comprehension in Asperger syndrome. *Brain and Language*, *113*(3), 124–134. https://doi.org/10.1016/j.bandl.2010.03.002

Hoddes, E., Dement, W. C., & Zarcone, V. (1972). The history and use of the stanford sleepiness scale. *Psychophysiology*, *9*, 150–155.

Howe, N. E. (2002). The origin of humor. *Medical Hypotheses*, *59*(3), 252–254. https://doi.org/10.1016/S0306-9877(02)00209-8

Jung, W. E. (2003). The Inner Eye Theory of Laughter: Mindreader Signals Cooperator Value. *Evolutionary Psychology*, *1*, 214–253. https://doi.org/10.1177/147470490300100118

Ku, L. C., Chang, Y. T., & Chen, H. C. (2020). How do extraverts process jokes? An event-related potential study on humor processing. *Brain and Cognition*, *141*, 105553. https://doi.org/10.1016/j.bandc.2020.105553

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

Loo, C. K., Martin, D. M., Alonzo, A., Gandevia, S., Mitchell, P. B., & Sachdev, P. (2011). Avoiding skin burns with transcranial direct current stimulation: Preliminary considerations. *International Journal of Neuropsychopharmacology*, *14*(3), 425–426. https://doi.org/10.1017/S1461145710001197

Manfredi, M., Proverbio, A. M., Donate, A. P. G., Vieira, S. M. G., Comfort, W. E., Andreoli, M. D. A., & Boggio, P. S. (2017). tDCS application over the STG improves the ability to recognize and appreciate elements involved in humor processing. *Experimental Brain Research*, *235*(6), 1843–1852. https://doi.org/10.1007/s00221-017-4932-5

Manfredi, M., Proverbio, A. M., Marques, L. M., Ribeiro, B., Morello, L. Y. N., & Boggio, P. S. (2019). Anodal transcranial direct current stimulation of MPFC enhances humor processing. *Social Neuroscience*, 1–15. https://doi.org/10.1080/17470919.2019.1674687

Martin, D. M., Liu, R., Alonzo, A., Green, M., & Loo, C. K. (2014). Use of transcranial direct current stimulation (tDCS) to enhance cognitive training: Effect of timing of stimulation. *Experimental Brain Research*, *232*(10), 3345–3351. https://doi.org/10.1007/s00221-014-4022-x

Metzuyanim-Gorlick, S., & Mashal, N. (2016). The effects of transcranial direct current stimulation over the dorsolateral prefrontal cortex on cognitive inhibition. *Experimental BrainResearch*, *234*, 1537–1544. https://doi.org/10.1007/s00221-016-4560-5

Mobbs, D., Greicius, M. D., Abdel-Azim, E., Menon, V., & Reiss, A. L. (2003). Humor modulates the mesolimbic reward centers. *Neuron*, *40*(5), 1041–1048. https://doi.org/10.1016/S0896-6273(03)00751-7

Moran, J. M., Wig, G. S., AdamsJrR. B., Janata, P., & Kelley, W. M. (2004). Neural correlates of humor detection and appreciation. *Neuroimage*, *21*(3), 1055–1060. https://doi.org/10.1016/j.neuroimage.2003.10.017

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. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x

Osovlanski, H., & Mashal, N. (2017). The effects of transcranial direct current stimulation on pragmatic processing. *Journal of Neurolinguistics*, *44*, 239–248. https://doi.org/10.1016/j.jneuroling.2017.07.002

Samson, A. C., Hempelmann, C. F., Huber, O., & Zysset, S. (2009). Neural substrates of incongruity-resolution and nonsense humor. *Neuropsychologia*, *47*(4), 1023–1033. https://doi.org/10.1016/j.neuropsychologia.2008.10.028

Samson, A. C., Zysset, S., & Huber, O. (2008). Cognitive humor processing: Different logical mechanisms in nonverbal cartoons—an fMRI study. *Social Neuroscience*, *3*(2), 125–140. https://doi.org/10.1080/17470910701745858

Saturnino, G. B., Puonti, O., Nielsen, J. D., Antonenko, D., Madsen, K. H., & Thielscher, A. (2019). SimNIBS 2.1: A comprehensive pipeline for individualized electric field modelling for transcranial brain stimulation. In S. Makarov, M. Horner, & G. Noetscher (Eds.), *Brain and* *human body modeling computational human modeling at EMBC 2018* (pp. 3–25). Springer.

Scheel, T., & Gockel, C. (2017). *Humor at work in teams, leadership, negotiations, learning and health*. Springer International Publishing.

Seibt, O., Brunoni, A. R., Huang, Y., & Bikson, M. (2015). The pursuit of DLPFC: Non-neuronavigated methods to target the left dorsolateral pre-frontal cortex with symmetric bicephalic transcranial direct current stimulation (tDCS). *Brain Stimulation*, *8*(3), 590–602. https://doi.org/10.1016/j.brs.2015.01.401

Slaby, I., Holmes, A., Moran, J. M., Eddy, M. D., Mahoney, C. R., Taylor, H. A., & Brunyé, T. T. (2015). Direct current stimulation of the left temporoparietal junction modulates dynamic humor appreciation. *Neuroreport*, *26*(16), 988–993. https://doi.org/10.1097/WNR.0000000000000456

Suls, J. M. (1972). A two-stage model for the appreciation of jokes and cartoons: An information-processing analysis. *The Psychology of Humor: Theoretical Perspectives and Empirical Issues*, *1*, 81–100.

Watson, K. K., Matthews, B. J., & Allman, J. M. (2006). Brain activation during sight gags and language-dependent humor. *Cerebral Cortex*, *17*(2), 314–324. https://doi.org/10.1093/cercor/bhj149

Wyer, R. S. Jr., & Collins, J. E. (1992). A theory of humor elicitation. *Psychological Review*, *99*(4), 663–688. https://doi.org/10.1037/0033-295X.99.4.663

Zempleni, M. Z., Renken, R., Hoeks, J. C., Hoogduin, J. M., & Stowe, L. A. (2007). Semantic ambiguity processing in sentence context: Evidence from event-related fMRI. *Neuroimage*, *34*(3), 1270–1279. https://doi.org/10.1016/j.neuroimage.2006.09.048