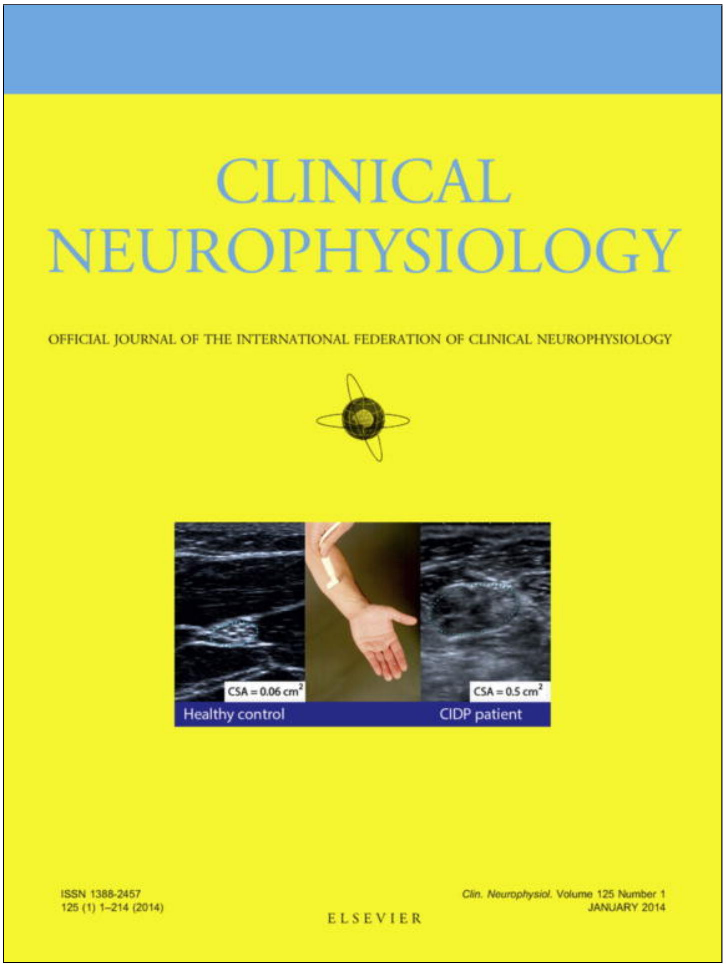
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Prefrontal oscillatory stimulation modulates access to cognitive control references in retrospective metacognitive commentary

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HIGHLIGHTS

- Efficient metacognitive commentary was observed following bilateral theta-rhythm stimulation.
- Increased bilateral prefrontal cortex theta-band connectivity is associated with enhanced working memory and confident metacognitive evaluations.
- Prefrontal cognitive control function may serve as a reliable predictor of retrospective metacognitive awareness.

ABSTRACT

Objective: We intended to examine how theta-rhythm transcranial alternating current stimulation (tACS) (versus sham non-active stimulation) modulated associations between working memory accuracy and later retrospective self-evaluation scores.
Methods: Healthy participants were required to complete a verbal working memory task while receiving tACS bilaterally over the dorsolateral prefrontal cortex (DLPFC) versus sham DLPFC stimulation. After completion of the online and post-stimulation working memory tasks, participants were asked to rate the level of success-confidence on the two preceding working memory tasks.
Results: As expected, online working memory accuracy was improved in the active bilateral DLPFC condition versus sham stimulation. Importantly, this working memory enhancement was related to post-stimulation self-evaluation scores.
Conclusions: Theoretically, our findings indicated that cognitive-control representations (e.g., working memory accuracy) could serve as the optimal *frame of reference* for later retrospective metacognitive judgments.
Significance: Noninvasive application of bi-frontal oscillatory currents might enhance functional connectivity between prefrontal regulatory components of working memory and retrospective monitoring in humans. Importantly, along with recent electrophysiological finding indicating interaction of tACS with ongoing oscillatory activity, our preliminary findings support the feasibility of utilizing tACS to treat theta-rhythm functional disconnectivity and related cognitive impairments in schizophrenia.

1. Introduction

In humans, the feeling-of-knowing (FOK) or metacognitive awareness can be conceptualized as a behavioral product of two possible metacognitive monitoring subsystems, prospective monitoring (i.e., predicting our "feeling of knowing" on a subsequent task) versus retrospective monitoring (i.e., evaluating our FOK on a previous task, Nelson, 1996). Recently, it has been suggested that dorsal-lateral prefrontal cortex sub-regions, such as the rostrolateral prefrontal cortex (rlPFC, spanning BA 46 to BA 10), may play a critical role in the accuracy of retrospective judgments associated with cognitive functions such as working memory performance (Fleming and Dolan, 2012). The contribution of rlPFC to retrospective metacognitive commentary may be to represent task uncertainty in a format that can be communicated to others (Fleming and Dolan, 2012; Yoshida and Ishii, 2006). In the present investigation, performance monitoring prefrontal mechanisms could be conceptualized as implicitly involved in integrating and maintain-

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ing task-relevant information related to a preceding relevant event (Fleming and Dolan, 2012). These cognitive-control representations pertaining to performance on a preceding working memory task serve to automatically facilitate later accurate metacognitive self-evaluations (Fleming and Dolan, 2012).

Therefore, we assessed retrospective success-confidence scores denoting "remembered" performance on a preceding verbal working memory task (verbal *n*-Back task, see Meiron and Lavidor, 2013). The recollection of performance was hypothesized to co-activate a monitoring component of working memory performance (Kane and Engle, 2002; Meiron and Lavidor, 2013) mediated by the dorsolateral prefrontal cortex (DLPFC). Additionally, since greater metacognitive accuracy may be related to prefrontal cortex connectivity (Fleming and Dolan, 2012), we administered "online" (during working memory activity) bilateral DLPFC transcranial alternating-current stimulation (tACS) in order to possibly enhance bilateral prefrontal working memory activity associated with later rlPFC-dependent retrospective metacognitive self-evaluations (Fleming and Dolan, 2012).

In our present experimental paradigm, we intended to examine active bilateral DLPFC tACS after-effects on retrospective self-evaluation success-confidence scores versus a sham stimulation condition. We chose oscillatory stimulation within the theta range (3.5–7.5 Hz) because recent EEG findings indicated that frontal theta power as well as theta phase synchronization between bilateral frontal regions is positively related to the integration of working memory associations into a unitary coherent memory representation (Wu et al., 2007). Importantly, we hypothesized that an electrical *exogenous boost* (Polania et al., 2012) of bilateral prefrontal theta oscillations during a verbal working memory task may interact with ongoing endogenous theta oscillations (Zaehle et al., 2010), hypothetically increasing prefrontal functional connectivity (Koenig et al., 2001) reflected in improved online working memory accuracy and higher post-stimulation retrospective metacognitive success-confidence scores.

In line with Meiron and Lavidor's (2013) suggestion that both right and left DLPFC contribute to verbal working memory function, we predicted that online bilateral tACS to the DLPFC would enhance online working memory accuracy versus a sham stimulation condition. Working memory improvement is hypothesized to stem from increased online theta-related functional connectivity in the prefrontal cortex via anterior regions of the corpus collasum that project to the rlPFC (Fleming and Dolan, 2012). Furthermore, we intended to show that the bilateral active tACS condition modulated the relationship between online working memory performance and retrospective self-evaluations scores. We predicted that these tACS modulations might indicate that retrospective metacognitive awareness is significantly related to both cognitive control circuitry (working memory accuracy) and sensorimotor circuitry (reaction times) only in the non-active sham stimulation. However, in the active bilateral tACS condition, increased bilateral DLPFC involvement (e.g., improved working memory performance) was hypothesized to result in self-evaluations that are significantly related to cognitive control circuitry, independent of embodied perceptual-motor working memory circuitry (Meiron and Lavidor, 2013). Promoting greater cognitive–control circuitry involvement during working memory activity, via bilateral prefrontal theta-rhythm tACS, is hypothesized to subsequently inhibit the involvement of early sensorimotor circuitry traces as a frame of reference in later retrospective metacognitive judgments. Finally, in line with Fleming and Dolan's (2012) theoretical model and our predictions related to human metacognitive awareness, we intended to address an ongoing theoretical question related to retrospective self-evaluation – to what extent does retrospective metacognition rely on earlier executive versus sensorimotor components of working memory function?

2. Methods

2.1. Participants

A total of 24 female participants completed the study (ages 19–27, $M = 21.5$, SD = 2.06). We avoided the inclusion of males due to previous imaging and brain-stimulation findings that indicated gender differences in prefrontal lateralization during verbal working memory performance and gender-dependent modulations of working memory accuracy during prefrontal anodal direct-current stimulation (Speck et al., 2000; Goldstein et al., 2005; Meiron and Lavidor, 2013). Twelve participants were in the active bilateral condition, and 12 participants were in the sham condition. We employed a between subject design because repetition of the same working memory paradigm in a within-subject design may facilitate learning effects related to improved response-selection strategies (Meiron and Lavidor, 2013). All participants fulfilled the following inclusion criteria: right-handed, normal/corrected to normal vision, healthy and free of medication. The exclusion criteria were metallic implants, learning disabilities, neurological/psychiatric history, skin disease, history of chronic migraines, first degree relative suffering from a psychotic disorder/epilepsy, and pregnancy. All participants gave their informed consent prior to study participation. Prior to the tACS manipulation all participants completed a short-version standard handedness questionnaire (Oldfield, 1971) validating them as consistent right-handers. Age and education were matched across stimulation conditions. In the active tACS condition mean age and education were 21.5 (SD = 1.73) and 12.67 (SD = 1.07), respectively. In the sham-stimulation condition mean age and education were 21.5 (SD = 2.43) and 12.47 (SD = 1), respectively. The study was approved by the ethics committee of Bar-Ilan University in accordance with the Declaration of Helsinki.

2.2. Online working memory task Stimuli

Stimulus-displays presented 42 different pairs of Hebrew word-nouns. Words within a word-pair were taken from different semantic categories (e.g., plants vs. animals). The words were one to two syllables long, and represented everyday objects that are easily activated and retrieved from long-term memory (Martindale, 1991). A post-experimental free recall procedure indicated that all target word-pairs were equally accessible (i.e., same probability of being recalled) indicative of inter-item associative-strength homogeneity (Deese, 1959; McClelland et al., 1986). The words were translated to Hebrew and back to English by bi-lingual translators to verify that the original word meaning was kept in Hebrew. The word pairs were presented with font David, size 70. The words appeared simultaneously, at the top (center alignment, 25% – *Y* axis) and bottom (center alignment, 75% – *Y* axis) locations, both centered horizontally. Words were bound to a particular display-location (see Fig. 1) to hypothetically induce greater event related theta synchronization during verbal working memory maintenance (Wu et al., 2007). Stimuli were visually displayed on a computer screen using E-Prime v2.0 presentation software (Psychology Software Tools, 2007). Screen size was 340 × 270 mm LCD. For further details on task stimuli see Meiron and Lavidor (2013).

2.3. Online working memory task procedure

Our verbal *n*-Back task was designed to recruit executive attention involvement (Kane and Engle, 2002) in two ways; first, we presented two possible targets within each *n*-Back study-display rather than one, secondly, we used everyday words instead of letters. These particular interfering task-components have been

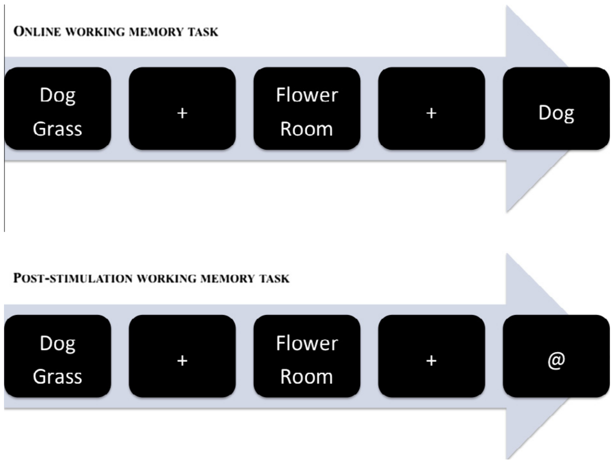

Fig. 1. An illustration of a two-study-display working memory trial. Top illustration displays a trial in the online working memory task. In the online working memory task, the last display (response-display) within a trial required participants to press a key if it was part of a word-pair that appeared two study-displays prior to response display. The bottom illustration displays a trial in the post-stimulation working memory task. In the post-stimulation working memory task, the response-display presents one out of two possible symbols requiring the participant to recall either the top ("@") or the bottom word ("%"), that appeared two study-displays prior to response-display.

shown to increase DLPFC activity (Kane and Engle, 2002) associated with executive attention's constant attempt to inhibit semantic retrieval-interference (Hicks and Starns, 2004) during item-recognition. We employed a 2-back task. Participants were instructed to study pairs of words within each two-second display for later 2-Back word recognition (e.g., correct recognition of an individual word that appeared within a pair of words two displays ago). An individual trial ends when a single word-probe (e.g. response-display) appears at fixation, unexpectedly, following the presentation of two to five pairs of words (e.g., study-displays). There were 12 different trials within one run of trials (see Fig. 1 for illustration of a two-study-displays trial). The entire working memory task consisted of four runs and five 30 s inter-run resting periods (48 trials, approx 17 min long). The four different runs displayed the same trials. The runs differed only in the presentation order of the trials and in their response-displays (probed-words). Within each run there were 12 different probed-words requiring the participants' response. 50% of the response displays were words taken from a two-back display (expected key-press response) and the other 50% were taken from non-target positions within a trial (e.g., one-Back or three-Back positions, no response expected). Correct responses and their corresponding reaction times were recorded by the computer. For a more detailed description of task procedure see Meiron and Lavidor (2013).

2.4. Online tACS conditions

Following scalp measurements, participants were randomly assigned to two different "online" (stimulation during working memory activity) tACS conditions. These conditions were (1) Active bilateral DLPFC stimulation, and (2) Sham DLPFC stimulation.

tACS was delivered by a battery driven Eldith DC-stimulator (neuroConn GmbH, Germany) using a pair of conductive-rubber electrodes placed in saline-soaked synthetic sponge. Both electrodes were 4×4 cm. All electrode positions were in accordance with the international 10–20 EEG system. The tACS bipolar montage for the active bilateral prefrontal condition was placed over the left and right DLPFC (corresponding to F3/AF3 midpoint and F4/AF4 midpoint EEG electrode locations, respectively). Both left and right prefrontal stimulation sites were located according to Fitzgerald et al. (2009) findings for optimal localization of the DLPFC (i.e., midpoint corresponding to halfway between F3 and AF3 electrode locations). The sham stimulation montage was the same as the active bilateral DLPFC montage. Alternating current stimulation was sinusoidal and current intensity was set to 1000 μA producing a peak current intensity of ±500 μA. Alternating current frequency was set at 4.5 Hz. In line with Griesmayr et al. (2010) suggestion that frontal theta activity (4–6 Hz) reflects working memory attentional demands, we chose a frequency value within this range to modulate ongoing prefrontal working memory activity. Importantly, stimulation parameters (e.g., 4.5 Hz versus frequency values between 5 Hz and 6 Hz) were predetermined following the assertion that they did not produce phosphenes or persisting skin sensation in a preliminary testing session with five healthy participants. 5400 cycles (20 min stimulation) were delivered in the active condition. Current was ramped up and down for 10 s and impedance was kept below 10 kΩ. In the sham stimulation, all parameters were the same as the active condition, however, only 90 cycles of stimulation were delivered (20 s). Following all experimental procedures, a debriefing was conducted to find out if participants felt the stimulation.

2.5. Post-stimulation working memory task

To examine the degree of cognitive control processing involvement in retrospective self-evaluations of working memory performance we employed a similar working memory task following the online working memory task. This immediate post-stimulation working memory task is considered to be more dependent on working memory cognitive control networks since it requires explicit recall of verbal working memory associations instead of verbal-item recognition (i.e., increased executive attention involvement, Kane and Engle, 2002). The target and study items were the same as in the online working memory task; however, in the response displays, one out of two possible abstract cues was presented, which directed the participant to explicitly recall (i.e., vocal response) a location-specific item that appeared two displays ago (see Fig. 1 for illustration of post-stimulation working memory trial). Vocal responses (i.e., spoken words) were recorded during the 2-second response displays by the computer. A more detailed illustration of the post-stimulation working memory task can be seen in Meiron and Lavidor (2013).

2.6. Retrospective success-confidence rating procedure

To examine metacognitive accuracy and possible stimulation effects on retrospective confidence judgments we employed a subjective retrospective success-confidence rating-scale procedure (Kirkpatrick et al., 2008; Fleming and Dolan, 2012). Accordingly, after completion of online and post-stimulation working memory tasks, participants were asked to rate the level of success-confidence (i.e., metacognitive self-evaluation, Schmitz et al., 2004) in the first online working memory task and on the 2nd post-stimulation working memory task on a scale of one-to-nine, where one reflects lowest level of success-confidence, and nine the highest level of success-confidence.

2.7. Post-stimulation discomfort measure

As a standard indication of the participants' level of discomfort, following the post-stimulation task, participants were asked to rate the pain-intensity they endured during the stimulation using a visual analogue scale (VAS), with scores ranging from 0 to 100 mm (Jensen et al., 1986).

2.8. Statistical analysis

In order to support reliability of metacognitive retrospective self-evaluation accuracy, using Pearson correlations, we examined the relationship between working memory accuracy scores (RT's of correct responses, and working memory accuracy scores – proportion of correct responses) and retrospective self-evaluation scores. To support our predictions related to bilateral prefrontal tACS working memory enhancement and higher retrospective success confidence we employed a multivariate analysis of variance (MANOVA) to examine the effect of tACS manipulation on online working memory accuracy and related post-stimulation self-evaluation scores. Additionally, to highlight the active bilateral DLPFC effect on online working memory performance, by employing additional ANOVA's, we needed to show that the active bilateral stimulation had no effect on "off-line" post-stimulation working memory performance (e.g., accuracy of vocal responses) versus a significant impact on online working memory performance (e.g., accuracy and RT's of correct key-press responses). Finally, using multiple regression analyses, we will examine which metacognitive "frame of reference" (Fleming and Dolan, 2012), such as working memory RT's versus working memory accuracy, had a more prominent association with retrospective self-evaluation scores within the active tACS condition versus sham condition.

3. Results

The stimulation was well tolerated, there were no side effects, and participants' reports indicated they could not discriminate between the active versus the sham stimulation condition (forced guessing was at chance level). During debriefing participants reported a minor tingling/itching sensation for the first 30 s of the stimulation. No phosphenes were reported. Discomfort levels were extremely low, and similar ($t(22) = .64$, $p = .53$) in both active (M = 8.3, SD = 14.03) and sham (M = 15.83, SD = 38) tACS conditions.

A one-way MANOVA indicated a significant tACS condition effect on online working memory accuracy ($F(1,22) = 7.4$, $p = .01$) and retrospective success-confidence scores ($F(1,22) = 5.18$, $p = .03$). Partial Eta Squared statistics showed effect sizes of 0.25 and 0.19 for working memory accuracy and self-evaluation scores, respectively. This analysis revealed that the active bilateral condition significantly enhanced online working memory accuracy (see Fig. 2) versus sham condition. RT's in the online working memory task were not significantly affected by tACS condition ($F(1,22) = 1.04$, $p = .31$). Mean RT's in the sham condition was 485.33 ms (SD = 88.27), and mean RT's for the active tACS was 457.19 ms (SD = 35.9). In regard to tACS impact on offline post-stimulation working memory accuracy a one way ANOVA indicated that the active tACS condition had no effect on post-stimulation working memory accuracy ($F(1,22) = 3.56$, $p = .072$). Significantly higher retrospective self-evaluation scores (denoting success confidence on the first online working memory task) were found in the active bilateral condition (M = 7.5, SD = .67) versus the sham condition (M = 6.66, SD = 1.07). Fig. 3 illustrates the distribution of retrospective self-evaluation scores as a function of tACS condition.

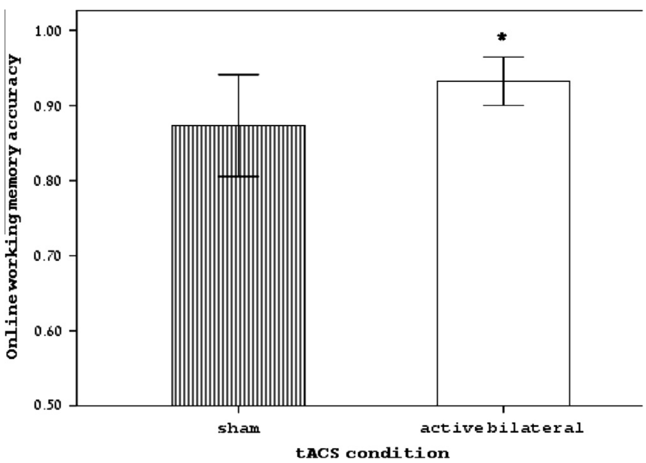

Fig. 2. Online working memory accuracy as a function of tACS condition. Active bilateral DLPFC condition enhanced accuracy. $^*p = .01$ versus sham condition. Error bars represent ±1 SD.

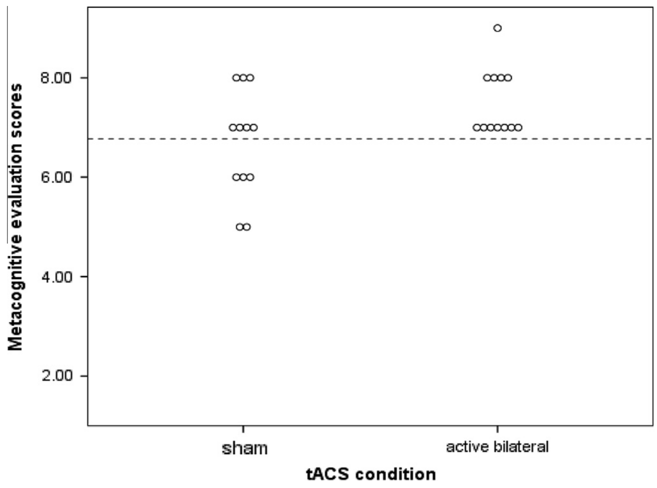

Fig. 3. Metacognitive self-evaluation score-distribution as a function of tACS condition. The Y-axis represents retrospective success-confidence scores in reference to online working memory performance. The horizontal line represents the mean-score of the entire sample (N = 24).

Across all participants, RT's and accuracy scores in the online working memory task were significantly related ($r = -.59$, $p = .002$, $r = .82$, $p < .001$, respectively) to retrospective self-evaluation scores. Next we examined the relationship of online working memory accuracy and RT's with retrospective self-evaluation scores within each tACS stimulation condition. In the sham condition, working memory accuracy and RT's were significantly related ($r = .82$, $p = .001$; $r = -.74$, $p = .006$, respectively) with retrospective self-evaluation scores. However, in the active bilateral DLPFC condition, only online working memory accuracy was significantly related ($r = .65$, $p = .02$) with retrospective self-evaluation scores (Fig. 4). A step-wise multiple regression analysis within each tACS condition was employed to examine which working memory performance measure (accuracy vs. RT's) was a better predictor of later self-evaluation scores. Regression models indicated that within both stimulation conditions (Sham: $R = .82$, $F(1,10) = 20.97$, $p = .001$: Active bilateral: $R = .65$, $F(1,10) = 7.5$, $p = .02$) online working memory accuracy represented the best predictor of retrospective metacognitive awareness. In contrast to the observed tACS condition effect on the online working memory performance, post-stimulation working memory accuracy and related retrospective self-evaluations (success-confidence ratings of the offline working memory task) were unaffected by tACS conditions. Interestingly, in the active bilateral condition, post-stimulation working memory accuracy was not related to later retrospective cognitive awareness.

In order to investigate which tACS condition produced more efficient (and hypothetically more accurate) retrospective metacognitive evaluations related particularly to the first online working memory task we also examined the relationship between post-stimulation working memory accuracy (second working memory task) and retrospective success-confidence scores associ-

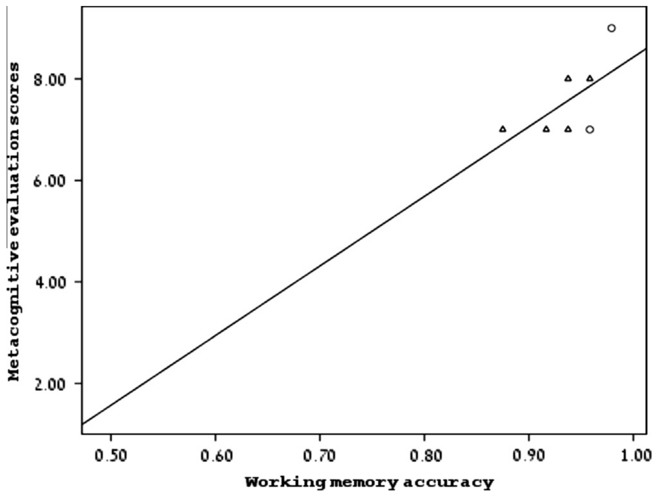

Fig. 4. An illustration of a significant relationship between enhanced working memory accuracy and later metacognitive judgments in the active bilateral DLPFC condition ($N = 12$). The *Y*-axis represents retrospective success-confidence scores. The *X*-axis represents working memory accuracy while receiving active bilateral DLPFC stimulation. Circles denote individual cases and triangles denote two cases or more.

ated with enhanced performance on the first on-line working memory task. Pearson's correlations indicated that in the active tACS condition's retrospective self-confidence scores of judging performance on the first online working memory task were not significantly related to accuracy scores on the second post-stimulation working memory task ($r = .48$, $p = .11$), but only significantly related to the relevant online working memory performance ($r = .65$, $p = .02$). However, in the in the sham condition participants self-confidence scores of judging performance on the first online working memory performance were related to both online working memory accuracy ($r = .82$, $p = .001$) and to the irrelevant post-stimulation working memory performance ($r = .62$, $p = .03$).

4. Discussion

In support of our retrospective judgment procedure as a valid assessment of metacognitive awareness, across all participants, we have seen that working memory accuracy scores as well as RT's of online working memory task were significantly related with later retrospective self-evaluation scores. These correlations remained significant within the sham condition. However, in the active bilateral condition, only online working memory accuracy remained significantly associated with retrospective metacognitive awareness. This finding implies that the executive component of working memory (i.e., working memory accuracy) may have been the "selected" frame of reference for later retrospective self-evaluations in the active bilateral DLPFC tACS condition. Theoretically, since prefrontal cognitive control loops are hypothesized to underlie executive verbal working memory function (reflected by response accuracy), we believe that enhancing this regulatory component of working memory may have contributed to later retrospective metacognitive commentary. Thus, the observed online working memory accuracy enhancement versus unaffected RT's in the active bilateral condition suggests that earlier encoding sensorimotor loops may not be essential for appropriate retrospective success-confidence judgments following prefrontal tACS. In support of this notion, multiple regression analysis indicated that working memory accuracy (versus RT's) in the online working memory task was the best predictor of retrospective success-confidence in both tACS conditions. However, theta-frequency tACS versus sham stimulation to the DLPFC seemed to enhance cognitive-control function, producing higher online working memory accuracy, which could be linearly associated with a more self-confident retrospective report of earlier working memory performance. More so, in the active bilateral condition, RT's were unrelated with retrospective self-evaluations scores, while the RT's in the sham condition were significantly related to retrospective self-evaluation scores. Therefore, particular working memory-related metacognitive frame of references, such as prefrontal cognitive control loops (i.e. executive component of working memory function), could be considered as reliable predictors of later retrospective metacognitive awareness across tACS conditions.

In regard to the possibility of increased correctness of metacognitive performance, our findings imply that retrospective self-evaluations of online working memory performance in the active tACS condition versus sham condition may have been more efficient, associated only with relevant preceding working memory performance (e.g., online working memory accuracy versus post-stimulation working memory accuracy). In the sham condition, participants' retrospective self-evaluations of performance on the online working memory task were significantly related to both on-line and post-stimulation working memory scores, indicating that their metacognitive self-evaluation scores were not solely based on the most relevant preceding working memory performance (performance on the first online working memory task), which may compromise accuracy of retrospective self-evaluations. Therefore, we believe that the active prefrontal stimulation might have increased access to relevant cognitive control representations associated with enhanced online working memory performance (first working memory task) independent of intervening post-stimulation working memory performance (second working memory task).

In the post-stimulation working memory task, unaffected working memory accuracy was related to retrospective metacognitive awareness only in the sham condition. However, online working memory enhancement in the active tACS condition and unaffected online working memory performance in the sham condition were both significantly associated with later retrospective metacognitive awareness. Although higher self-evaluation scores in the active tACS condition may have resulted from improved preceding online working memory performance, online working memory enhancement observed in the active bilateral prefrontal stimulation might have facilitated efficient metacognitive awareness via increased connectivity between metacognitive performance-monitoring network activity (BA 46 area of rlPFC), and increased earlier activity in working memory executive attention circuitry (i.e. DLPFC, BA 9 and BA46). In support, unaffected post-stimulation working memory accuracy-scores in the active bilateral condition were unrelated to retrospective cognitive awareness of performance on the preceding post-stimulation working memory task. This finding distinguishes metacognitive awareness of online working memory accuracy from metacognitive awareness of off-line, post-stimulation working memory accuracy. We suggest that the active bilateral condition may have induced maximum theta-rhythm connectivity during the online working memory task. Thus, the propensity for increasing prefrontal functional connectivity associated with cognitive control engagement during the post-stimulation working memory task may have been depleted. Additionally, since the post-stimulation working memory task required explicit recall (versus implicit recognition in the online working memory task), enhanced prefrontal theta working memory-activity may have reduced access to long-term memory (LTM) associations mediated by different and more posterior neural frequencies (i.e., alpha band, see Khader et al., 2010). Thus, other functional frequencies might mediate critical frame-of-references for later retrospective judgments on earlier working memory challenges that include response modalities (such as explicit recall in the post-stimulation working memory task) related to LTM processes.

Our results indicated that online working memory accuracy might be considered a valid predictor of retrospective metacognitive awareness. Both stimulation conditions promoted the independent encoding-role of online cognitive-control loops (represented by online working memory accuracy) into retrospective metacognitive awareness circuitry. As a result of bilateral prefrontal theta-rhythm stimulation, during the online working memory task, DLPFC-rlPFC networks may have been sensitized to produce more coherent cognitive-control references than sham-condition cognitive control references for later metacognitive judgments. Bilateral prefrontal theta stimulation is also hypothesized to facilitate the selection of metacognitive responses (Fleming and Dolan, 2012). More interestingly, the rlPFC, which is known to correlate with metacognitive report-confidence (Fleming and Dolan, 2012), is hypothesized to play a critical regulatory role during retrospective success-confidence self-evaluations. It has been suggested that the rlPFC utilizes information from limbic sub-systems (e.g., anterior cingulate cortex) related to online adjustments in task performance (Fleming and Dolan, 2012). Hence, our bilateral DLPFC stimulation protocol may have improved functional connectivity between dorsal rlPFC areas and the anterior cingulate cortex, which in turn may have enhanced an online executive component of later retrospective metacognitive awareness. In order to support our hypothesis, future neuro-imaging studies would need to examine active bilateral stimulation effects on retrospective metacognitive neural activity. More so, to strengthen our particular prefrontal stimulation procedure as possibly promoting metacognitive awareness, future studies are needed to examine the effects of other stimulation-frequencies (e.g., alpha vs. gamma vs. theta) and other stimulation sites on retrospective FOK.

In conclusion, in the present investigation the relationship between induced working memory enhancement and retrospective metacognitive commentary could be attributed to efficient metacognitive performance-monitoring function achieved by increased DLPFC involvement in the active tACS condition during earlier executive working memory maintenance (Kane and Engle, 2002). More so, since it is hypothesized that performance-monitoring metacognitive neural networks reside within the DLPFC (Fleming and Dolan, 2012), we believe we may have facilitated the abstract encoding of decision-related information, which is considered to be independent of response-modality (Fleming and Dolan, 2012). Most importantly, the integrity of these regulatory prefrontal mechanisms is compromised in patients suffering from abnormal prefrontal activity (e.g., schizophrenia patients, Tan et al., 2006). Thus, the present tACS findings may shed light on novel noninvasive stimulation treatment possibilities. A recent study that utilized the same executive working memory task (same as the first online working memory task in the present study) to examine executive attention deficits in schizophrenia patients (Meiron et al., in press) found that the patients' working memory deficits were significantly related to psychosis severity and functional capacity. Hence, by possibly improving this particular executive working memory function in schizophrenia patients via bi-frontal tACS we could indirectly promote more efficient metacognitive reality monitoring processes in "active" psychotic patients (e.g., suffering from disruptive delusions and hallucinations), and most importantly, we may be able alleviate illness severity and promote return to everyday function in individuals suffering from schizophrenia. Therefore, further investigation with clinical criterion groups is warranted to assess our proposed theta-frequency prefrontal stimulation as a potential tACS treatment protocol in targeting particular dysexecutive psychopathologies related to metacognitive awareness dysfunction in humans.

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