

Altered action-related modulation of visual size perception in schizophrenia: Associations with avolition and exploratory effects of supramarginal gyrus stimulation

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Abstract

Background

Schizophrenia is associated with disturbances in the integration of perceptual and action-related information, which may contribute to abnormalities in goal-directed behavior and negative symptoms. Affordance-related information provides a framework for examining how action-related object properties influence perception. However, whether the extraction of action-related object information and its influence on visual size processing are altered in schizophrenia, and whether such alterations are related to avolition, remains unclear.

Methods

Twenty-seven patients with schizophrenia and 27 healthy controls completed an Ebbinghaus size-matching task crossing tool identity (table-tennis paddle vs. wooden hammer) and handle orientation (right- vs. left-facing). The paddle–hammer contrast was used as an operational index of paired-object action relations within an affordance framework, whereas handle orientation indexed graspability-related processing. In a separate exploratory within-subject crossover experiment, 16 healthy participants received online stimulation of the left supramarginal gyrus (SMG) or vertex during the same perceptual task.

Results

In healthy controls, both affordance manipulations modulated perceived size. The Group $\times$ Tool interaction was significant ($F(1,52) = 14.21, p < .001, \eta p^2 = .215$): controls showed smaller perceived size for paddles than hammers, whereas patients did not. The signed paddle–Hammer score correlated positively with SANS avolition ($r = .445, N = 27, p = .020$), with greater avolition corresponding to a less negative paddle–hammer contrast. A significant TMS $\times$ tool type interaction was observed ($F(1,15) = 5.30, p = .036, \eta p^2 = .26$); the paddle–hammer difference was no longer significant after left SMG stimulation but remained detectable after stimulation over the vertex.

Conclusion

Schizophrenia was associated with altered modulation of visual size by paired-object action relations, and individual differences in this modulation were associated with avolition. The exploratory TMS findings provide preliminary causal evidence that the left SMG may contribute to paired-object action-related modulation of visual size. These findings suggest that altered integration of action-related object information into visual processing may be relevant to negative symptoms in schizophrenia.

Background

Abnormalities in action–perception integration have been reported in schizophrenia and have been interpreted within embodied and phenomenological frameworks as reflecting disturbances in self-experience and the relationship between the individual and the environment ^{1–3}. Consistent with these perspectives, previous studies ^{4,5} proposed that disturbances in the ecological relationship between the self and the environment may impair the perception of affordances. Affordances refer to action possibilities specified by the relationship between an object's properties and an individual's action capabilities^{6,7}. Because affordances can be extracted automatically from object perception, they provide a well-defined interface through which action-related information may influence ongoing visual processing. This raises a specific and unresolved question: whether affordances can automatically modulate visual size perception, and whether this modulation is altered in schizophrenia.

Using a stimulus–response compatibility paradigm, Sevos reported an absence of the facilitation of visual judgments by object graspability in patients with schizophrenia⁸. Eye-tracking studies have similarly suggested altered extraction of action-related information during action-naming tasks⁹. These findings suggest that automatic processing of action-related object properties may be altered in schizophrenia. In contrast, other studies have reported preserved aspects of action–perception processing, including motor simulation during action-verb comprehension and plasticity of peripersonal space following tool use ^{10,11}. More recently, Schmitter et al. found relatively preserved action-related neural responses during simple hand movements but reduced active–passive differentiation during tool-use actions or when actions were accompanied by bimodal sensory feedback¹². Together, these findings suggest that action–perception integration in schizophrenia may become increasingly vulnerable as the informational demands of an action increase.

The present study used an Ebbinghaus paradigm in which a central ping-pong ball was surrounded by table-tennis paddles or wooden hammers, with the handle facing right or left. The paddle–ball pairing was expected to evoke a stronger paired-object action relation (i.e., hitting a ball with a paddle) than the hammer–ball pairing; thus, the paddle–hammer contrast was intended to index paired-object affordance, whereas handle orientation provided an index of graspability-related processing. Prior studies suggest that both handle orientation and object–action relations can influence action-related processing, although such effects may be shaped by visuospatial salience, semantic context, and task demands^{13–15}. These forms of affordance differ in representational demands: paired-object affordance depends more strongly on functional and relational knowledge about how objects can be used together, whereas graspability affordance is specified more directly by the geometry and orientation of an individual object ^{16–20}. Whether these forms of action-related information differentially modulate visual size perception in schizophrenia remains unknown.

Negative symptoms have been associated with impaired action prediction and object-size processing during observed actions²¹, while avolition has been linked to deficits in action–outcome learning²².

Negative symptoms have also been associated with prior-dependent perceptual biases^{23, 24}. If schizophrenia-related alterations in affordance processing vary across representational levels, the severity of negative symptoms—particularly avolition—may therefore be associated with the magnitude of affordance-related modulation of visual illusions.

The supramarginal gyrus (SMG) has been implicated in tool use and object-use processing²⁵, whereas structural and functional abnormalities in this region have been associated with negative symptoms in schizophrenia^{26, 27}. Together with preliminary causal evidence from healthy participants, this provides a rationale for examining the SMG as a candidate substrate of affordance-related visual modulation. Building on prior Ebbinghaus work showing that action-related context can modulate perceived size²⁸, we tested whether paired-object and graspability affordances differentially modulate perceived size in schizophrenia and healthy controls, and whether individual differences in this modulation are associated with negative symptoms, particularly avolition. We additionally conducted an exploratory active-controlled rTMS study of the left SMG in healthy participants to examine whether disrupting this region alters tool-use-related size modulation, providing a normative causal reference rather than a direct model of schizophrenia pathology.

We hypothesized that:

1. Compared with healthy controls, patients with schizophrenia would show an attenuated paddle–hammer contrast, whereas the orientation-related effect on perceived size would remain detectable.
2. Greater avolition would be associated with a less negative paddle–hammer contrast.
3. Online TMS targeting the left SMG would attenuate the modulation of perceived size by paired object–action relations.

Methods

Participants

Patients with schizophrenia were recruited from Shenzhen Kangning Hospital. All patients met DSM-5 criteria for schizophrenia as determined by experienced psychiatrists and were receiving stable antipsychotic treatment at the time of testing. A target of 30 patients was set a priori as a feasibility sample. Recruitment stopped after 30 patients had been enrolled; three were unable to understand or perform the behavioral task and provided no usable data, yielding a final sample of 27 patients.

The final schizophrenia sample comprised 15 men and 12 women, with a mean age of 32.96 years (SD = 11.59, range = 16–58), mean education of 11.48 years (SD = 5.05, range = 6–24), mean illness duration of 9.59 years (SD = 7.09, range = 1–26), and mean age at illness onset of 23.37 years (SD = 6.76, range = 15–41). Patients were excluded for recent ECT/MECT (< 1 month), recent changes in antipsychotic medication, another major psychiatric disorder, neurological disease or traumatic brain injury, severe or

unstable medical illness, current substance or alcohol use disorder, clinically significant cognitive impairment or inability to understand the procedures, or uncorrectable visual impairment. An overview of the study design is shown in Fig. 1.

Clinical assessment

Negative and positive symptoms were assessed using the Scale for the Assessment of Negative Symptoms (SANS) and the Scale for the Assessment of Positive Symptoms (SAPS). The Chinese versions of the SANS and SAPS have demonstrated good reliability and validity in Chinese patients with schizophrenia²⁹. In the present sample, the mean SANS and SAPS total scores were 43.15 (SD = 14.18, range = 19–77) and 39.85 (SD = 9.47, range = 30–69), respectively.

Healthy controls

Twenty-seven healthy controls were recruited from the local community and group-matched to patients on age and years of education. The group comprised 13 men and 14 women, with mean age of 31.96 years (SD = 12.60) and mean education of 11.96 years (SD = 4.81). Groups did not differ significantly in age, education, or sex (all p s > .58). All participants were right-handed and had normal or corrected-to-normal vision. Written informed consent was obtained from all participants. The study was approved by the Institutional Ethics Committee of Shenzhen Kangning Hospital (approval No. 2025-K022-01) and conducted in accordance with the Declaration of Helsinki.

TMS experiment

Sixteen healthy participants (8 men and 8 women; age range, 18–25 years; mean age = 21.4 years, SD = 2.33) were recruited from the local community in Dalian, China. All had normal or corrected-to-normal vision and provided written informed consent before the experiment.

Behavioral experiment

Design, stimuli, and procedure. The behavioral experiment used a $2 \times 2 \times 2$ mixed design: group (schizophrenia vs. healthy control) was between-subjects; tool (table-tennis paddle vs. wooden hammer) and orientation (right- vs. left-facing) were within-subjects (Fig. 1). Perceived target size was measured by a size-matching task and expressed as percentage deviation from physical size: $100 \times (\text{matched size} / \text{target size} - 1)$; 0% indicated an exact match, and positive/negative values indicated perceived enlargement/shrinkage. A central ping-pong-ball target was surrounded by four inducers (paddle or hammer) above, below, left, and right. Inducer head diameter was 2.2° (handle excluded), and the minimum edge-to-edge distance to the target was 0.1° , maintained by adjusting inducer positions with target size. Handles faced left or right. A comparison circle appeared below the central stimulus,

centered 6.28° from screen center. Target and initial comparison-circle sizes were sampled independently; target diameter averaged 1.47° (SD = 0.17°). Trial conditions were pseudorandomized. Luminance, contrast, and color were matched across the paddle and hammer inducers using the SHINE toolbox. The detail of stimuli is shown in Fig. 1.

Before the main task, participants completed an 8-trial object-identification task (each object twice per orientation) and achieved 100% accuracy. Four practice size-matching trials were administered and excluded from analysis; no baseline or catch trials were included. Participants were told the target was a ping-pong ball and to maintain fixation; eye movements were not monitored or restricted. Each trial began with a 2-s fixation cross, followed by simultaneous presentation of the target–inducer display and comparison circle. Participants adjusted the comparison circle with up/down arrow keys until it matched the target; each keypress changed its diameter by 1 pixel (~ 0.025°). All participants were right-handed and responded with the right hand. No confirmation key was required; the next trial began automatically, with a maximum trial duration of 10 s. In the later version, there were 76 trials in two blocks with a mandatory 1-min break. Each tool × orientation condition appeared 19 times, distributed as evenly as possible across blocks. Trial order was pseudorandomized. The experiment was programmed and administered using PsychoPy(Fig. 2A)..

Behavioral data analysis

The final size of the comparison circle was expressed as a percentage deviation from the physical target size using $100 \times (\text{matched size} / \text{target size} - 1)$. Thus, 0% indicates an exact physical-size match, and negative values indicate perceived underestimation. The tool-related contrast was defined as Paddle – Hammer, and the orientation contrast as Right – Left. Only participants with complete behavioral data were included (27 patients and 27 controls). No participant-level or trial-level outliers were excluded, and no data were missing. Each condition contained 19 trials in the final procedure. Behavioral data were analyzed using a $2 \times 2 \times 2$ mixed ANOVA, followed by simple-effects analyses of significant interactions. Normality and homogeneity of variance were checked. Because group variances for the principal tool contrast were unequal, a Welch-type sensitivity analysis was conducted for the between-group contrast; the pattern of results remained unchanged. Analyses were performed using Matlab R2023b.

Clinical correlates analysis

To examine whether the primary behavioral effect was associated with clinical symptoms, we explored the relationship with avolition, given its links to goal-directed action and action-related perception. Avolition was assessed using the three descriptive items of the SANS avolition/apathy subscale (grooming and hygiene, impersistence at work or school, physical anergia). Item scores were averaged to generate a composite avolition score, with higher scores indicating greater severity. Pearson correlations were then computed between the primary behavioral index and the composite avolition score in patients with schizophrenia.

TMS procedure

TMS was delivered using a PowerMag Clinical 100 stimulator (Mag & More, Berlin, Germany) with a figure-of-eight coil. Stimulation was guided by a Visor2 neuronavigation system (ANT Neuro, Berlin, Germany) using individual structural MRI scans. The left supramarginal gyrus (SMG) target was defined from group-level activation obtained in a previous task-fMRI experiment using the same paradigm (MNI coordinates: -45, -36, 39). Detailed information on the functional localization procedure and activation results is provided in the Supplementary Materials. This coordinate was spatially close to previously reported SMG TMS targets^{30,31}. The control condition involved stimulation over the vertex (Cz).

Each trial was accompanied by a five-pulse train delivered at 10 Hz and 80% of the individual motor threshold, with the train initiated concurrently with stimulus onset. The stimulation parameters (10 Hz, 5 pulses, 400 ms) were selected based on established online rTMS protocols, including prior studies targeting the SMG during object-use and manipulation tasks³¹. Participants completed two TMS sessions separated by at least 1 week, with stimulation order counterbalanced across participants. Each session comprised 88 trials (Fig. 2B).

TMS experiment analysis

TMS effects were assessed using repeated-measures ANOVA with TMS site, stimulus type, and handle orientation as within-subject factors. Mauchly's test was used to check sphericity, and Greenhouse–Geisser correction was applied when needed. Significant interactions were followed by paired-sample *t*-tests, with effect sizes reported as partial eta-squared (ηp^2) for ANOVA and Cohen's *d* for *t*-tests.

Results

Behavioral results

A $2 \times 2 \times 2$ mixed ANOVA revealed a significant Group $\times$ Tool interaction, $F(1, 52) = 14.21, p < .001, \eta p^2 = .215$, indicating that the effect of Tool differed between groups (Fig. 3A). Follow-up comparisons showed a significant paddle–hammer difference in healthy controls, with perceived size being lower for the paddle than for the hammer, whereas this difference was not observed in patients with schizophrenia. The main effect of Orientation was also significant, $F(1, 52) = 31.04, p < .001, \eta p^2 = .374$ (Fig. 3B). The Group $\times$ Orientation interaction was not significant, $F(1, 52) = 1.75, p = .192$, corresponding to a between-group difference of 0.72 percentage points (95% CI [-0.39, 1.83]). The remaining interactions were not significant (all $ps \geq .516$); full ANOVA results are provided in Supplementary Table S1.

Bonferroni-corrected paired-sample *t*-tests showed a tool-related reduction in perceived size in healthy controls (mean difference = -1.49 percentage points, $t(26) = -4.14, p < .001, dz = -0.80$, 95% CI [-2.23, -0.75]) but not in patients (mean difference = 0.14 percentage points, $t(26) = 0.59, p = .563, dz = 0.11$, 95%

CI [- 0.35, 0.63]). The orientation effect was observed in both patients (- 1.15 percentage points, $t(26) = - 6.93$, $p < .001$) and controls (- 1.87 percentage points, $t(26) = - 3.62$, $p = .001$). Full effect-size and confidence-interval estimates are provided in Supplementary Tables S2 and S3.

Clinical correlates

Following the significant Group $\times$ Tool interaction, we examined clinical correlates of the tool-related perceptual effect in patients (Fig. 3C). SANS avolition was positively associated with the paddle–Hammer perceptual contrast ($r = .445$, $N = 27$, 95% CI [.078, .706], $p = .020$). After controlling for age and illness duration, the partial correlation remained significant ($r = .480$, 95% CI [.105, .736], $p = .015$), and the regression model was significant ($\beta = 0.603$, $SE = 0.230$, $t = 2.63$, $p = .015$, 95% CI [0.128, 1.078]; $R^2 = .406$, adjusted $R^2 = .329$). Because healthy controls showed a negative paddle–Hammer contrast (paddle < hammer), the positive association with avolition indicates a less negative paddle–Hammer contrast in patients with greater avolition, consistent with a relative weakening of the paddle-induced size reduction rather than a uniform reduction in the absolute contrast. Partial correlations were additionally calculated while controlling for age and illness duration. A linear regression model was used to examine the association after covariate adjustment, and a sensitivity analysis controlling for positive symptoms was conducted. Leave-one-out analyses were performed to assess the robustness of the correlation. Detailed leave-one-out sensitivity analysis, descriptive statistics, correlation and regression results, partial correlation controlling for positive symptoms, and robustness analyses are provided in Supplementary Tables S4–S8.

3.3. TMS results

A repeated-measures ANOVA revealed significant main effects of tool type, $F(1, 15) = 6.38$, $p = .023$, $\eta p^2 = .30$, and handle orientation, $F(1, 15) = 17.42$, $p = .001$, $\eta p^2 = .54$, as well as a significant TMS $\times$ stimulus type interaction, $F(1, 15) = 5.30$, $p = .036$, $\eta p^2 = .261$ (Fig. 4). The complete ANOVA results, including the TMS main effect and all interaction terms, are provided in Supplementary Table S9. The TMS $\times$ tool type interaction indicates that the effect of tool type differed as a function of stimulation site. The handle-orientation effect did not show evidence of a corresponding TMS-related modulation. Together, these findings suggest that perturbation of the left SMG altered the perceptual effect associated with stimulus type, whereas evidence for a TMS-related change in handle-orientation processing was limited.

Discussion

The present study examined whether action-relevant information influences perceived size in schizophrenia. In healthy participants, handle orientation and paired object–action relations modulated the Ebbinghaus illusion, suggesting that distinct forms of action-relevant context can shape visual size judgments. In patients, the Group $\times$ Tool interaction indicated a between-group difference in the paddle–Hammer contrast: healthy controls showed a negative contrast (paddle < hammer), whereas patients showed a descriptively positive contrast (paddle > hammer), with no significant within-group simple effect. This pattern suggests an altered influence of the paired-object action relation on perceived size.

Greater avolition was associated with a more positive paddle–Hammer contrast, although causality cannot be inferred. The exploratory TMS findings provide preliminary causal evidence relevant to this interpretation. Together, these findings suggest a possible alteration in particular forms of action–perception integration in schizophrenia, while alternative explanations remain.

Previous studies using a range of experimental paradigms have shown that humans can automatically process task-irrelevant action-related properties of objects and facilitate the processing of perceptual attributes relevant to potential actions^{13, 14, 17}. Within the Ebbinghaus illusion paradigm, Chen et al.²⁸ reported that replacing the central target with a manipulable object, such as a basketball, reduced the magnitude of the illusion, suggesting that manipulability can exert a top-down influence on perceived size. Their manipulation concerned the central target rather than the peripheral inducers and therefore provides complementary evidence to the present study. Extending this work, we found peripheral tool identity (paddle vs. hammer) and handle orientation modulated the Ebbinghaus illusion, consistent with paired object–action and graspability-related influences, respectively. This pattern suggests that visual size perception can be modulated not only by properties specifying how an individual can directly interact with a single object, but also by paired-object action relation.

The dissociation between graspability-related and paired-object action relation effects may reflect differences in the neural and computational demands of these forms of affordance processing^{16, 17, 32–34}. The dorsal visuomotor system, including superior parietal regions, has been implicated in processing spatial object properties relevant to actions such as reaching and grasping^{19, 20}, whereas inferior parietal regions, particularly the SMG, have been implicated in tool-related action processing and action observation^{25, 34–36}. Consistent with this literature, the behavioral dissociation observed in the present study is compatible with the possibility that graspability-related and paired object–action relation affordances draw on partially distinct visuomotor processes. The rTMS findings provide further evidence relevant to this interpretation: stimulation over the left SMG reduced the paddle–hammer difference associated with paired-object action relations, whereas the orientation-related effect showed no significant TMS-related modulation. This pattern is broadly consistent with previous TMS studies implicating the left SMG in tool-related action processing^{30, 37}. One TMS study found that stimulation of the left SMG selectively delayed the selection of appropriate grasp orientations for tool use, whereas grasping for transport was unaffected³⁶. Together, these findings are compatible with a contribution of the left SMG to the processing of paired-object action relations, while suggesting that its role may be more closely related to relational action information than to affordance processing in general.

The orientation-related modulation observed in patients with schizophrenia may partly reflect the salient geometry of the elongated handle oriented toward the dominant hand. Such object-centered cues provide information relevant to hand posture and grasp direction through relatively direct visuomotor mappings^{19, 20, 38}. Because handle geometry and graspability were not independently manipulated, however, the effect may also reflect more general visuospatial or visuomotor processing of object orientation. Importantly, elongated object structures engage dorsal visuomotor regions involved in

grasping, with aspects of their representation overlapping with grasp-related action processing^{19, 20,38}. Given that elongated structures are also naturally compatible with grasping, their perceptual processing may therefore provide relatively direct access to action-relevant information. At most, these findings raise the hypothesis that simple object-centered action cues may be less affected than relational action information in schizophrenia.

The association between avolition and paired object–action modulation may reflect a specific level of action representation rather than a general perceptual deficit. Unlike graspability cues, which can be specified relatively directly from the geometry of a single object, paired object–action relations require linking multiple objects with their functional use and potential goal-directed actions^{16–18}. This relational process may place greater demands on the integration and maintenance of action representations, which have been implicated in negative symptom, including avolition^{21,22,39,40}. This interpretation converges with predictive action–perception accounts. Schmitter et al.¹² found altered action-related neural differentiation during tool-use actions and bimodal feedback, but not during simple unimodal hand movements. Although their paradigm involved self-generated actions rather than static perceptual judgments, these findings are compatible with greater vulnerability when action information must be integrated across sources or into a more functionally rich action representation. This possibility may help explain why paired-object action modulation, rather than graspability-related orientation, was associated with avolition in the present study. However, because relational demands were not directly measured and the association was correlational, the present findings cannot distinguish between altered relational action representations, altered weighting of action-related information, and downstream differences in its integration into perception.

If replicated, this pattern could inform future studies of action–perception coupling. Existing interventions have incorporated training that links action goals with relevant objects and tools^{41,42}. Building on these approaches, future studies could test whether training or neuromodulation targeting object–action relational processing alters paired object–action modulation and avolition.

The SMG is a plausible neural substrate for the perceptual and clinical associations observed here. Previous studies have reported abnormalities involving the SMG and broader inferior parietal regions in schizophrenia, including associations with negative symptom severity, although these findings have involved different hemispheres and neuroimaging measures^{26,27}. The present TMS findings provide complementary evidence that perturbing the left SMG, relative to vertex stimulation, alters the influence of paired object–action relations on visual size perception in healthy participants. Together, these findings raise the possibility that SMG-related action–perception processing contributes to the altered paired object–action modulation associated with avolition. Direct evidence linking these processes in schizophrenia will require studies that assess SMG function and action–perception measures within the same patient sample. A registered clinical trial has also directly targeted the left SMG with navigated iTBS for negative symptoms in schizophrenia (NCT06642675), providing an emerging translational context for the present findings.

Several limitations should be noted. First, although luminance, contrast, and color were matched using the SHINE toolbox, the naturalistic paddle and hammer stimuli could not be fully matched for texture and spatial-frequency characteristics. Thus, stimulus-driven perceptual differences cannot be completely excluded as an alternative contribution to the observed effects. Second, TMS was delivered concurrently with stimulus onset, whereas different components of affordance processing may unfold over distinct time windows. The absence of a significant effect on orientation-related modulation therefore does not establish that the SMG is uninvolved in graspability-related processing. Third, the exploratory TMS experiment involved a small sample of healthy participants ($n = 16$). The findings therefore provide preliminary causal evidence in a normative sample and cannot by themselves establish whether the same mechanism is altered in schizophrenia or is related causally to negative symptoms.

Conclusion

The present findings suggest that in patients with schizophrenia, graspability-related affordance processing and its influence on perceived size did not show a reliable group difference, whereas paired object–action relation processing may be altered. Greater avolition was associated with a more positive paddle–Hammer contrast, consistent with an altered expression of the paired-object action relation effect, although this association does not establish causality. Exploratory TMS findings provide preliminary evidence that the left SMG may be involved in tool-related action processing, raising the possibility that the SMG and its network may be relevant to both avolition and altered paired-object action processing. These findings may inform future behavioural training of tool-use functions or neuromodulation targeting the SMG, but clinical utility remains to be established.

Declarations

Ethics approval and consent to participate

The behavioral and clinical components of the study were approved by the Ethics Committee of Shenzhen Kangning Hospital (Approval No. 2025-K022-01). The TMS experiment was approved by the relevant Institutional Ethics Committee of Liaoning Normal University. All procedures were conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before participation in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Ethics approval

This study was approved by the Ethics Committee of Shenzhen Kangning Hospital (Approval No. 2025-K022-01).

Informed consent

Written informed consent was obtained from all participants before participation in the study.

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Author Contribution

Jian Xu: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, and writing—original draft. Jixue Bao: Conceptualization, Clinical assessment, investigation, and data collection. Shen Zhang, Yi Zhang: Investigation and data collection. Jin Chen, Xiaoxuan Liu: Clinical assessment, investigation, and data collection. Xiaojian Jia: Conceptualization, supervision, project administration, and writing—review and editing.

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Use of generative AI tools

Generative artificial intelligence (AI) tools were used solely for language editing and polishing of the manuscript. The authors reviewed and verified all AI-assisted text and remain fully responsible for the content, interpretation, and conclusions of the manuscript. AI tools were not used for study design, data collection, data analysis, or scientific decision-making.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request, subject to applicable ethical and institutional restrictions.

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Figures

Experimental design and stimuli

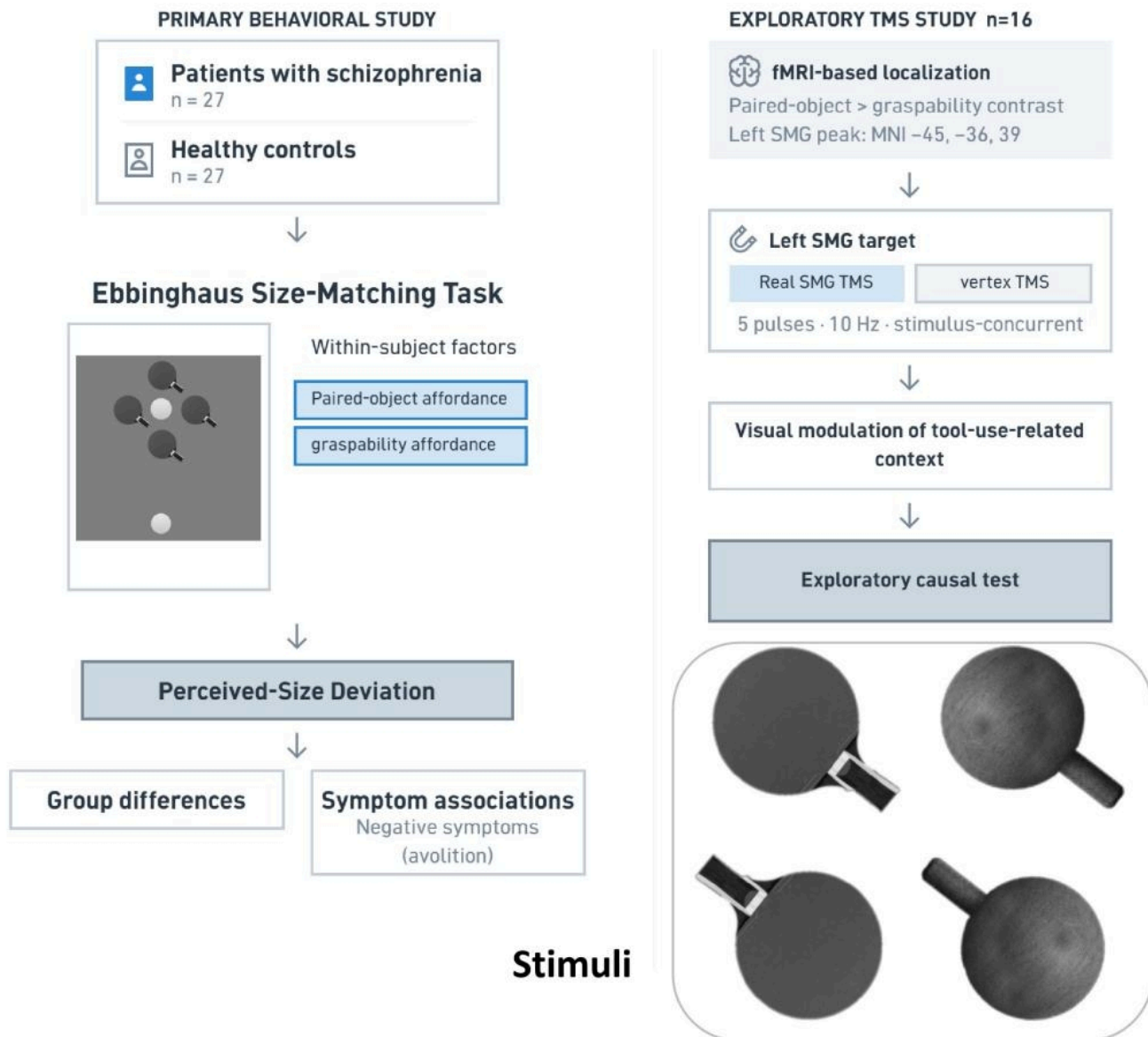


Figure 1

Study design and experimental stimuli. Overview of the behavioral and TMS experiments. The behavioral experiment included 27 patients with schizophrenia and 27 healthy controls and examined the effects of tool identity and handle orientation on perceived size. The exploratory TMS experiment included 16 healthy participants and compared online stimulation of the left supramarginal gyrus (SMG) with vertex stimulation. Peripheral inducer stimuli used in the Ebbinghaus size-matching task. The left and right columns show the table-tennis paddle and wooden hammer, respectively; the upper and lower rows show right- and left-oriented handles, respectively.

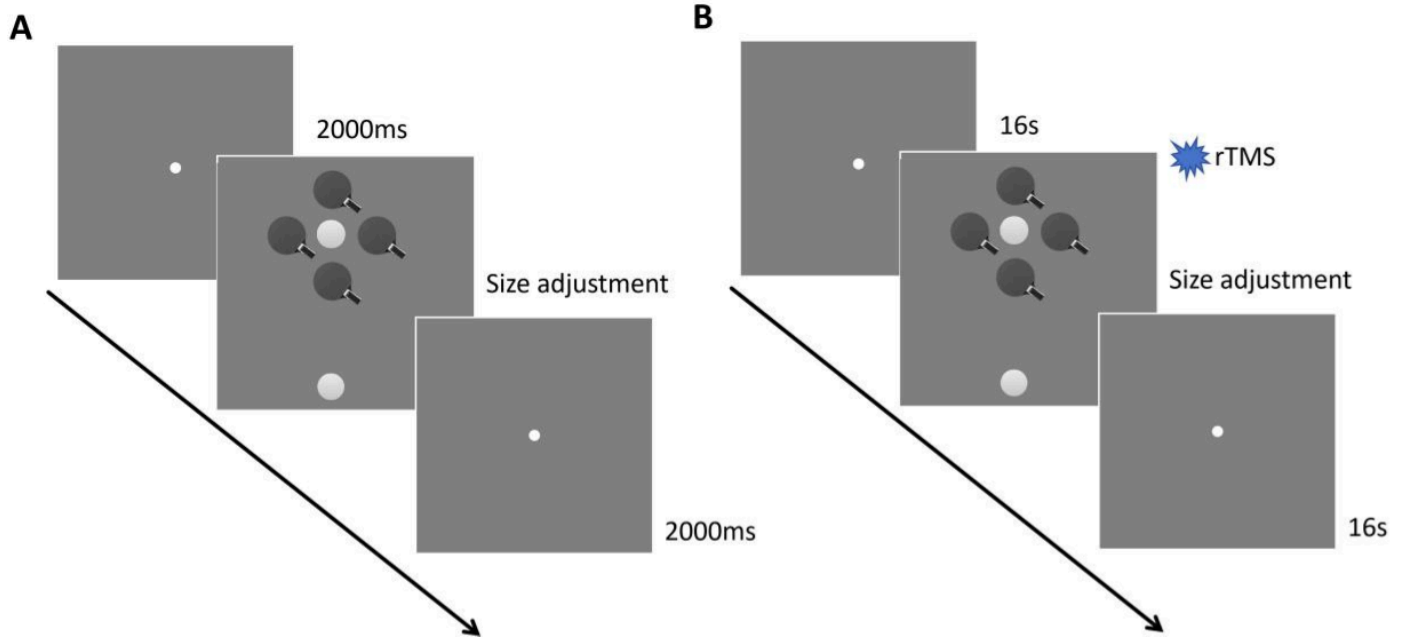


Figure 2

Experimental design. (A) Behavioral experiment. Numbers indicate stimulus presentation durations, and participants adjusted the size of the comparison circle using the response keys before the next trial began automatically. (B) TMS experiment. The lightning symbol indicates TMS delivered synchronously with stimulus presentation.

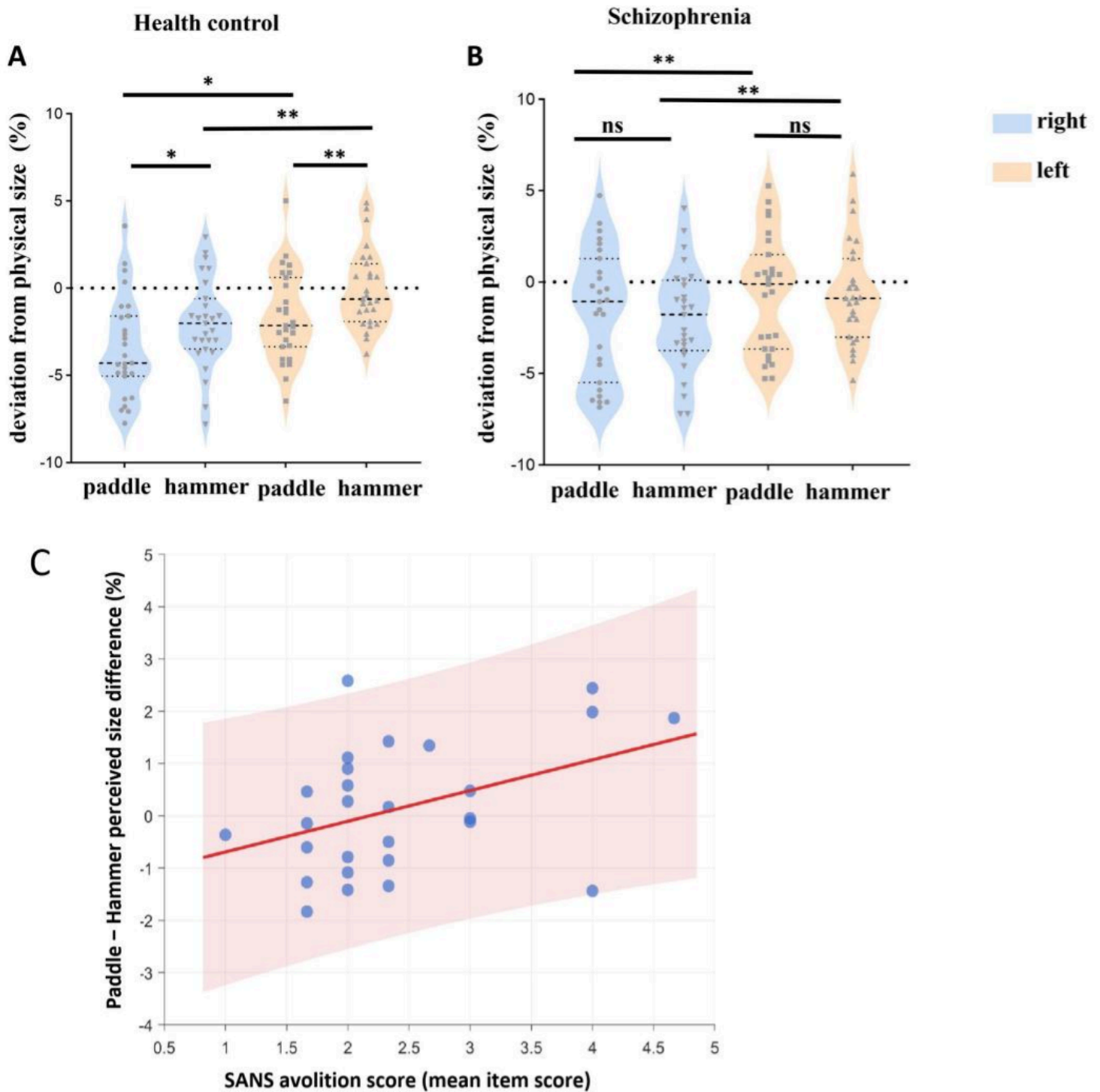


Figure 3

Behavioral results and association with avolition. (A) Deviation from physical size (%) as a function of tool (paddle vs. hammer) and handle orientation (right vs. left) in healthy controls. (B) Same analysis in patients with schizophrenia. (C) Association between the paddle–hammer perceived size difference (%) and SANS avolition scores in patients with schizophrenia (N = 27). The shaded area indicates the 95% prediction interval. * $p < .05$, ** $p < .01$, *** $p < .001$.

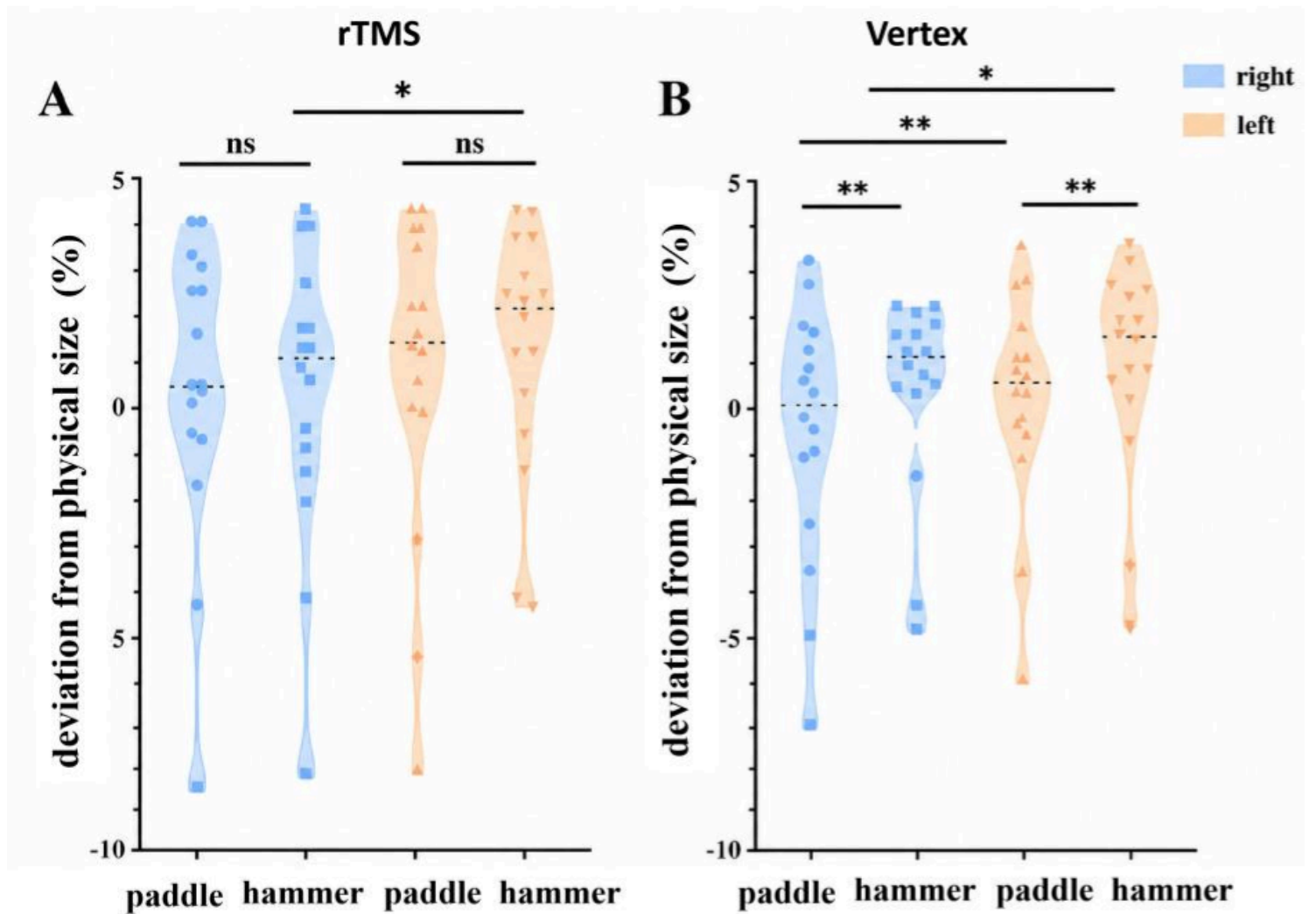


Figure 4

Effects of TMS perturbation and stimulation on tool-related perceptual modulation. (A) TMS applied over the left SMG. (B) TMS applied over the vertex. * $p < .05$, ** $p < .01$, *** $p < .001$; ns, not significant.

Supplementary Files

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- [XuSupplementarytables.xlsx](#)