Object Category Modulation of Sensory Dominance Effect in Cross-Modal Conflict

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Abstract

The sensory dominance effect refers to the phenomenon where the brain prioritizes processing information from a particular sensory modality when confronted with multisensory information. The cognitive processing level hypothesis posits that sensory dominance effects are determined by different cognitive processing levels, with visual dominance manifesting at early perceptual processing stages and auditory dominance at late response processing stages. However, existing research has not investigated how intermediate processing levels—situated between early and late stages—within the cognitive processing hierarchy influence sensory dominance effects. The present study manipulated object category differences at this intermediate processing level and employed a 2-1 mapping paradigm to examine, across three experiments, how object category representations (intermediate between early perceptual and late response levels) modulate sensory dominance effects at the response level. Experiment 1 results demonstrated that object category differences can modulate sensory dominance effects at the response level: when category differences were small, visual dominance was observed, whereas when category differences were large, auditory dominance emerged. Experiment 2 results indicated that this effect's emergence is independent of varying processing depths of visual stimuli, confirming its specificity to the visual modality. Experiment 3 inhibited the category-processing brain region (the left anterior temporal lobe) using transcranial direct current stimulation technology, and the results revealed that the auditory dominance effect at the response level disappeared. These findings demonstrate that the intermediate processing level of object category representation within the cognitive processing hierarchy modulates sensory dominance effects, thereby refining the cognitive processing level hypothesis's explanation of sensory dominance effects.

Full Text

Preamble

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Response:
(1) Using a cross-modal 2-1 mapping paradigm, cognitive processing levels were divided into preresponse and response levels. By manipulating the degree of object category differences, this study investigated from a behavioral perspective how intermediate processing levels regulate sensory dominance effects in cross-modal conflict.
(2) Through transcranial electrical stimulation, the left anterior temporal lobe—a brain region critical for object category processing—was modulated, providing causal evidence for the influence of object category representations on sensory dominance in cross-modal conflict.
(3) The findings refine the existing cognitive processing level hypothesis regarding sensory dominance effects by demonstrating that representational modes at intermediate processing levels—situated between early perceptual and late response stages—also influence sensory dominance.

2. Have you published or submitted any articles using the same data as this study? If yes, please attach them for review.

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Response: No.

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4. Did you report and analyze effect sizes (e.g., Cohen's d for t-tests, ^{2} or ^{2}p for ANOVA, standardized regression coefficients)? (Many studies mechanically report effect sizes without necessary analysis or explanation, such as whether the effect size is small, medium, or large, or its theoretical/applied significance.) (Search "effect size calculator" on Google for convenient apps. For explanations of effect sizes in Chinese, see: http://journal.psych.ac.cn/xlkxjz/CN/abstract/abstract1150.shtml; in English, see: http://www.uccs.edu/lbecker/effect-size.html) Did you report 95% CIs for statistical analyses (e.g., 95% CI for differences, correlation/regression coefficients)? For CI calculation and graphing, see https://thenewstatistics.com/itns/esci/

Response: Effect sizes were reported and analyzed: Cohen's d for t-tests, ^{2}p for ANOVA, and 95% CIs for statistical analyses.

5. Please state the planned and actual sample sizes. If they differ, please explain why. The problem of low statistical power due to insufficient sample sizes is widespread in psychological research. We recommend explaining in the Methods section how you determined your sample size, based on a justified effect size, desired power, and reporting the software or program used. See https://osf.io/5awp4/ for guidance.

Response: G*Power 3.1 (Faul et al., 2007, 2009) was used to estimate sample size. Based on Chen and Zhou (2013), where the cross-modal conflict effect had Cohen's d = 0.70, we set α err prob = 0.05 and power (1 - β err prob) = 0.8, yielding a total sample size of 18. Therefore, the experimental sample size should be no fewer than 18 participants. To ensure adequate statistical power, Experiment 1's three sub-experiments included 30 participants each for analysis, and Experiment 2 included 34 participants for analysis.

6. [Note: This question appears to be about reporting p-values, but the text is garbled in the original. Based on context, it likely asks about precise p-value reporting vs. reporting as $p < 0.001$, and Bayesian factors.]

Response: Precise p-values were reported.

7. To ensure completeness of data reporting, if any data were excluded from statistical analyses, were they reported in the text? What were the reasons? How would the results change if these data were included? How were missing data handled? Were any individual items from scales removed? Why? How would results change if these items were included? Were any measured items or variables not reported? Why? Please indicate where in the paper this information appears.

Response: Since participants' mean accuracy exceeded 95% across all experiments, error trials were not analyzed. Only correct trials were analyzed, and trials with reaction times deviating more than 3 SDs from the mean were excluded. (See Methods section in the main text.)

8. Were any experimental materials, scales, or questionnaires that have not undergone peer review and validation attached at the end of the file for review? If not, please explain why. If this article is published, are you willing to share these materials with other researchers?

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Response: [Not answered in original]

Object Categories Modulate Sensory Dominance Effects in Cross-Modal Conflict

Abstract

Sensory dominance refers to the phenomenon where the brain prioritizes processing information from certain sensory channels when faced with multisensory inputs. The cognitive processing level hypothesis posits that sensory dominance effects are determined by different cognitive processing stages, with early perceptual processing exhibiting visual dominance and late response processing exhibiting auditory dominance. However, existing research has not examined how intermediate processing levels—situated between early and late stages—influence sensory dominance effects. This study manipulated object category differences at the intermediate processing level and employed a 2-1 mapping paradigm across three experiments to investigate how object category representations, positioned between early perceptual and late response levels, affect sensory dominance in cross-modal conflict.

Experiment 1 found that object category differences modulated sensory dominance at the response level. When category differences were small, visual dominance emerged; when category differences were large, auditory dominance emerged. Experiment 2 demonstrated that this effect was unrelated to different depths of visual stimulus processing, confirming that the effect is specific to the visual channel. Experiment 3 used transcranial direct current stimulation (tDCS) to inhibit the left anterior temporal lobe—a brain region critical for object category processing. Results showed that auditory dominance at the response level disappeared. These findings indicate that object category representations at the intermediate processing level of cognitive hierarchy modulate sensory dominance effects, thereby refining the cognitive processing level hypothesis's explanation of sensory dominance in cross-modal conflict.

Keywords: object categories, visual dominance effect, auditory dominance effect, preresponse level, response level

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1. Introduction

Multisensory integration is the process of combining information from multiple sensory channels into a coherent and meaningful percept, which helps us perceive external information more quickly and effectively and is crucial for our survival and development (Stein & Stanford, 2008; Tang et al., 2016). When confronted with different information from multiple sensory channels, our brain does not assign equal weight to each channel, leading certain sensory channels to be processed preferentially and resulting in sensory dominance effects (Callan et al., 2015; Hirst et al., 2018; Zhou et al., 2022). The most common forms of sensory dominance are visual dominance and auditory dominance. Visual dominance effects have shown that when visual flashes and auditory sounds are presented simultaneously, participants tend to respond only to the visual flashes while ignoring the auditory sounds (Colavita, 1974; Wang et al., 2021). Auditory dominance effects have demonstrated that when the number of visual flashes mismatches the number of auditory sounds, participants' judgments of visual flash count are influenced by the auditory sounds (Shams et al., 2000; Wang et al., 2020). However, how sensory dominance effects arise and what factors constrain them remain important questions in this field (Keil, 2020; Hirst et al., 2020).

Researchers have proposed various theories to explain the mechanisms underlying sensory dominance effects. The attentional orienting hypothesis suggests that information from attended sensory channels is processed preferentially (Amedi et al., 2017), but it cannot explain classic auditory dominance effects. The channel appropriateness hypothesis posits that the sensory channel most suitable for a specific task drives perception (Hirst et al., 2020), yet it neglects the influence of top-down prior knowledge or expectations (Wang et al., 2019). The mathematically-based Bayesian causal inference model combines relative sensory signal reliability, quantitative prior expectations, and prior expectations of common origin to determine the emergence of sensory dominance effects (Odegaard et al., 2016; Wozny et al., 2008). Although this model can specifically explain auditory dominance effects well, its explanation of visual dominance effects is limited. These theoretical hypotheses emphasize external signal influences while neglecting the role of internal processing levels.

The fact that different experimental paradigms produce different sensory dominance effects also suggests that external signals merely serve as triggering media, while internal processing plays a decisive role (Robinson et al., 2016). Consequently, researchers have explained the occurrence of sensory dominance effects from the perspective of cognitive processing itself, proposing the processing level hypothesis. This hypothesis suggests that sensory dominance effects are determined by cognitive processing levels, with early perceptual processing levels exhibiting visual dominance and late response processing levels exhibiting auditory dominance (Chen & Zhou, 2013; Li et al., 2019).

The cognitive processing level hypothesis can be divided into early perceptual processing levels and late response processing levels (Wang et al., 2006), or alternatively into preresponse levels (including perceptual and semantic processing) and response levels (Chen & Zhou, 2013). However, Chen et al. (2010) argued that there exists an intermediate module processing level for cognitive processing between early perceptual and late response levels. Existing research on sensory dominance effects under the cognitive processing level framework has primarily focused on early perceptual processing levels (Koppen et al., 2009) and late response processing levels (Kato & Konishi, 2006; Mayer et al., 2009), while neglecting how intermediate processing levels influence sensory dominance effects at the response level. Moreover, previous studies on sensory dominance effects under the cognitive processing level framework used visual images of political figures and celebrities along with their corresponding auditory names as stimuli. They found that at the preresponse level, conflict caused by visual distractors when attending to auditory stimuli was significantly greater than conflict caused by auditory distractors when attending to visual stimuli, demonstrating visual dominance. In contrast, the response level showed auditory dominance. However, the distinction between political figures and celebrities in that study has a certain social nature and requires long-term learning and experience. Furthermore, face processing is specific and differs from processing other category stimuli such as animals and tools (Martin & Chao, 2001). Therefore, whether the sensory dominance effects observed at different processing levels in that study have generality remains to be investigated.

Object category processing occurs at an intermediate processing level between early perceptual and late response levels (Bi et al., 2016; Martin, 2007). Previous studies have shown that object recognition largely depends on processing object shape (Li et al., 2024; Morgenstern et al., 2024). When objects have high structural similarity, recognition is faster and more accurate; when structural similarity is low, accuracy decreases. Animal objects are highly similar in visual appearance and functional properties, with small structural differences, whereas tool objects are more diverse visually and functionally, showing larger structural differences (Wiggett et al., 2009). Vogler and Titchener (2011) used animal and tool objects as experimental materials and found that animal objects were identified significantly faster and more accurately than tool objects. Consistently, Laws (2000) found that participants showed stronger visual and auditory processing abilities for animal objects compared to tool objects. Given these differences in processing different object categories, this study investigated how internal representations influence sensory dominance effects by manipulating object category representation differences at this intermediate cognitive processing level.

This study employed a 2-1 mapping paradigm to manipulate object category differences and examine their impact on sensory dominance effects in cross-modal conflict. Experiment 1 manipulated the degree of object category differences to explore whether and how they influence sensory dominance effects.

Experiments 1a~c used stimuli with small category differences (Experiment 1a: wild animals vs. domestic animals), moderate category differences (Experiment 1b: vehicles vs. household tools), and large category differences (Experiment 1c: animals vs. musical instruments). Since object category processing occurs after early perceptual processing levels, it may influence the output of late response processing levels. Experiment 1 hypothesized that object categories would affect sensory dominance at the response level. Given that visual stimuli presented as pictures reach perceptual representation faster than auditory names, Experiment 2 changed visual stimuli from pictures to words based on Experiment 1c to investigate whether the effect of object categories on response-level sensory dominance is specific to the visual channel rather than different depths of visual processing. Although picture and word processing speeds differ, both can be processed before the response level. Therefore, Experiment 2 hypothesized that the presentation modality of object categories would not affect sensory dominance at the response level. Since the left anterior temporal lobe is responsible for object category processing (Binney et al., 2018; Diez et al., 2017; Wong & Gallate, 2012), Experiment 3 further used transcranial direct current stimulation (tDCS) to inhibit the left anterior temporal lobe based on Experiment 1c, causally investigating the influence of object categories on sensory dominance. Experiment 3 hypothesized that inhibiting object category processing would not affect the preresponse level but would alter sensory dominance at the response level.

2. Experiment 1: The Influence of Object Category Differences on Sensory Dominance

2.1 Methods

2.1.1 Participants G*Power 3.1 (Faul et al., 2007, 2009) was used to estimate sample size. Based on Chen and Zhou (2013), where the cross-modal conflict effect had Cohen's d = 0.70, we set α err prob = 0.05 and power (1 - β err prob) = 0.8, yielding a total sample size of 18. Therefore, the experimental sample size should be no fewer than 18 participants. To ensure adequate statistical power, Experiment 1a recruited 31 university students, with 1 excluded (for target response accuracy $<$ 80%; due to the task's simplicity, remaining participants had mean accuracy above 90%), leaving 30 participants (10 male, 20 female, mean age 20.97 years, SD = 2.04). Experiment 1b recruited 32 participants, with 2 excluded, leaving 30 participants (12 male, 18 female, mean age 20.43 years, SD = 1.79). Experiment 1c recruited 30 participants (12 male, 18 female, mean age 20.33 years, SD = 1.92). All participants had normal or corrected-to-normal vision and were unaware of the experimental purpose. All were right-handed, signed informed consent before the experiment, and received compensation afterward. This study followed the Declaration of Helsinki and was approved by ×× University.

2.1.2 Apparatus and Materials The experiment was conducted in a quiet, dimly lit laboratory. The experimental program was written in Matlab 2014b using the Psychtoolbox toolbox and run on a Windows 7 operating system. Stimuli were presented on a 27-inch LCD monitor (refresh rate 60 Hz, resolution 1920 × 1080). Participants sat approximately 60 cm from the monitor. The background color was set to gray (RGB: 127, 127, 127). A fixation cross "+" (1.5º × 1.5º visual angle) at the center of the gray screen remained present throughout the experiment.

Visual stimuli were six selected and validated pictures from a standard outline drawing database (Snodgrass & Vanderwart, 1980). In Experiment 1a, pictures were wild animals (elephant, lion, seal) and domestic animals (hen, duck, cat). In Experiment 1b, pictures were vehicles (car, airplane, ship) and household tools (iron, kettle, chair). In Experiment 1c, pictures were animals (lion, elephant, seal) and musical instruments (guitar, piano, flute). Picture materials (5º × 6º visual angle) were presented at the screen center for 450 ms. Auditory stimuli were the Chinese names of the six pictures, presented simultaneously with visual stimuli through headphones (ATH-WS99) at 65 dB for 450 ms.

2.1.3 Experimental Design and Procedure All experiments used a 2 (attention modality: visual vs. auditory) × 3 (congruency: congruent vs. preresponse incongruent vs. response incongruent) within-subjects design. In Experiment 1a, the task was to judge whether the attended channel presented a wild or domestic animal. In Experiment 1b, participants judged whether the attended channel showed a vehicle or household tool. In Experiment 1c, participants judged whether the attended channel presented an animal or musical instrument. For participants, all pictures and names were potential targets requiring responses throughout the experiment.

Pictures and names constituted three congruency conditions: (1) Congruent condition: picture and name were the same object (e.g., seeing a lion and hearing "lion" in Experiment 1c); (2) Preresponse incongruent condition: picture and name did not correspond to the same object but mapped to the same response key (e.g., seeing a lion and hearing "seal" in Experiment 1c); (3) Response incongruent condition: picture and name corresponded to different response keys (e.g., seeing a lion and hearing "guitar" in Experiment 1c).

Attention modality was presented in a block design, with three congruency trial types randomly mixed within each block. In each block, participants were instructed to attend to either vision or audition while ignoring stimuli from the other modality. Participants were required to fixate on the central cross throughout the experiment. After a 500 ms central fixation, visual and auditory stimuli were presented simultaneously for 450 ms. Participants had 3000 ms to respond, followed by a 500 ms inter-trial interval before the next trial began.

There were 24 blocks with 12 trials each, with three congruency trial types randomly presented. Visual-attention and auditory-attention blocks alternated. Each block began with a 2000 ms instruction indicating which modality to attend to. There were six experimental conditions with 48 trials each, totaling 288 trials. To maintain participants' alertness, three rest breaks were included. The formal experiment lasted approximately 30 minutes, preceded by a 3-minute practice session.

[Figure 1: see original paper] shows stimulus examples and the experimental procedure for Experiment 1c. Audiovisual stimuli constituted three conditions: congruent (identical audiovisual stimuli), preresponse incongruent (different stimuli but same response key), and response incongruent (different stimuli and different keys). Preresponse conflict = RT in preresponse incongruent condition - RT in congruent condition; Response conflict = RT in response incongruent condition - RT in preresponse incongruent condition.

2.1.4 Data Analysis First, since participants' mean accuracy exceeded 95% across all experiments, error trials were not analyzed. Only correct trials were analyzed, and trials with reaction times deviating more than 3 SDs from the mean were excluded. Second, differences in reaction times across audiovisual conditions were used to distinguish conflict effects at preresponse and response levels: the difference between preresponse incongruent and congruent conditions represented preresponse-level conflict, while the difference between response incongruent and preresponse incongruent conditions represented response-level conflict. Finally, by comparing conflict effects when attending to vision versus audition, sensory dominance was determined: when visual conflict was significantly greater than auditory conflict, visual dominance emerged; when auditory conflict was significantly greater than visual conflict, auditory dominance emerged. The study reported ^{2}p and Cohen's d as effect size indices for F-tests and t-tests, respectively.

2.2 Results

Experiments 1a~c examined animal objects with small category differences (Experiment 1a: wild vs. domestic animals), tool objects with moderate differences (Experiment 1b: vehicles vs. household tools), and animal and musical instrument objects with large differences (Experiment 1c: animals vs. musical instruments). In Experiment 1, audiovisual stimuli constituted three conditions: congruent, preresponse incongruent, and response incongruent. The difference between preresponse incongruent and congruent conditions represented preresponse-level conflict, while the difference between response incongruent and preresponse incongruent conditions represented response-level conflict. By comparing conflict caused by auditory distractors when attending to vision versus visual distractors when attending to audition, we investigated sensory dominance effects at preresponse and response levels and how object categories influenced them.

In Experiment 1a (Figure 2A), at the preresponse level, visual conflict (94.13 ms) was significantly greater than auditory conflict (48.03 ms), $t(29) = 3.78$, $p < 0.001$, Cohen's $d = 0.69$, 95% CI = [21.13, 71.06]. At the response level, visual conflict (33.64 ms) was significantly greater than auditory conflict (-3.47 ms), $t(29) = 2.81$, $p = 0.009$, Cohen's $d = 0.51$, 95% CI = [10.11, 64.13]. These results indicate that both at preresponse and response levels, visual conflict was significantly higher than auditory conflict, demonstrating visual dominance.

In Experiment 1b (Figure 2B), at the preresponse level, visual conflict (86.55 ms) was significantly greater than auditory conflict (48.56 ms), $t(29) = 2.58$, $p = 0.015$, Cohen's $d = 0.47$, 95% CI = [7.88, 68.09]. At the response level, there was no significant difference between visual and auditory conflict, $t < 1$. These results show visual dominance at the preresponse level but no sensory dominance at the response level.

[Figure 2: see original paper] shows results for Experiments 1 and 2. Panels A–C display results for Experiments 1a–c; Panel D shows the distribution of sample means from resampling the sensory dominance index (difference between auditory and visual conflict) for each experiment; Panel E shows results for Experiment 2. Note: ***$p < 0.001$,*** *$p < 0.01$,* $p < 0.05$, Bonferroni corrected.

Error bars represent standard errors.

In Experiment 1c (Figure 2C), at the preresponse level, visual conflict (86.08 ms) was significantly greater than auditory conflict (36.28 ms), $t(29) = 4.33$, $p < 0.001$, Cohen's $d = 0.79$, 95% CI = [26.29, 73.32]. At the response level, auditory conflict (34.33 ms) was significantly greater than visual conflict (3.91 ms), $t(29) = 2.53$, $p = 0.017$, Cohen's $d = 0.46$, 95% CI = [5.82, 55.03]. These results indicate visual dominance at the preresponse level and auditory dominance at the response level.

To further compare the strength of sensory dominance effects across the three sub-experiments, we calculated a sensory dominance index for each by subtracting visual conflict from auditory conflict (positive values indicate auditory dominance; negative values indicate visual dominance).

For the preresponse level, a one-way ANOVA showed no significant differences across the three sub-experiments, $F < 1$. A one-sample t-test against 0 revealed $t(89) = 6.05$, $p < 0.001$, Cohen's $d = 0.64$, 95% CI = [29.98, 59.28], indicating consistent visual dominance at the preresponse level regardless of object category.

For the response level, the ANOVA showed a significant main effect of experiment, $F(2, 87) = 6.00$, $p = 0.004$, $^{2}p = 0.12$. Post-hoc analyses with Bonferroni correction revealed that the sensory dominance index in Experiment 1c was significantly greater than in Experiment 1a, $t(59) = 3.46$, $p = 0.002$, Cohen's $d = 0.89$, 95% CI = [21.05, 114.03]. No significant differences were found between Experiment 1b and Experiments 1a or 1c, $t_1(59) = 1.77$, $p = 0.24$; $t_2(59) = 1.69$, $p = 0.28$. One-sample t-tests against 0 showed that Experiment 1b did not differ significantly from 0, $t < 1$, indicating no sensory dominance effect; Experiment 1a was significantly less than 0, $t(29) = 2.81$, $p = 0.009$, Cohen's $d = 0.51$, 95% CI = [10.11, 64.13], indicating visual dominance; and Experiment 1c was significantly greater than 0, $t(29) = 2.53$, $p = 0.017$, Cohen's $d = 0.46$, 95% CI = [5.82, 55.03], indicating auditory dominance. These results demonstrate that sensory dominance at the response level is modulated by object categories: visual dominance emerges when category differences are small, whereas auditory dominance emerges when category differences are large.

To more intuitively observe and validate the results, we plotted the distribution of sensory dominance indices from 1000 resamples using standard bootstrap methods (Figure 2D). The x-axis represents the preresponse-level sensory dominance index, and the y-axis represents the response-level index. All three experiments were distributed primarily to the left of the x-axis 0 point. However, Experiment 1a was distributed below the y-axis 0 point, Experiment 1b near the y-axis 0 point, and Experiment 1c above the y-axis 0 point. These results further confirm that object categories modulate sensory dominance at the response level.

3. Experiment 2: Excluding the Influence of Visual Stimulus Presentation Modality

Although Experiment 1 demonstrated that object categories influence sensory dominance at the response level, all visual stimuli were presented as pictures. Picture stimuli can express object appearance structure and access perceptual representations earlier (Baddeley & Hitch, 2017; Potter & Fox, 2009; Wiggett et al., 2009), while auditory stimuli access semantic representations earliest. According to the sensory-semantic model (Higdon et al., 2024; Roberts et al., 2022), pictures can express more subtle sensory codes—for example, various postures of cats correspond to the single semantic code "cat." Picture stimuli have processing advantages over word or sound stimuli (Hockley & Bancroft, 2011). Therefore, visual stimulus presentation modality might have influenced Experiment 1's results. To address this, Experiment 2 converted visual stimuli from pictures to words based on Experiment 1c to examine whether presentation modality affects response-level sensory dominance. According to classic cognitive theory (Sternberg, 2000), semantic processing occurs between perceptual and response levels, so both pictures and words can complete semantic processing before the response level. Experiment 2 hypothesized that even when visual stimulus format changed from pictures to words, response-level sensory dominance would remain unaffected.

Experiment 2 recruited 35 university students, with 1 excluded (using the same criteria as Experiment 1), leaving 34 participants (15 male, 19 female, mean age 21 years, SD = 1.92). All had normal or corrected-to-normal vision, were unaware of the experimental purpose, right-handed, signed informed consent, and received compensation afterward. The study followed the Declaration of Helsinki and was approved by ×× University.

The apparatus was identical to Experiment 1c. Visual stimuli differed from Experiment 1c: picture stimuli were replaced with word stimuli in SimSun font ($5^{\text{o}} \times 6^{\text{o}}$ visual angle).

The experimental design and procedure were identical to Experiment 1c.

Data analysis followed the same method as Experiment 1c.

3.2 Results In Experiment 2 (Figure 2E), at the preresponse level, visual conflict (83.29 ms) was significantly greater than auditory conflict (31.94 ms), $t(33) = 5.45$, $p < 0.001$, Cohen's $d = 0.93$, 95% CI = [32.16, 70.54]. At the response level, auditory conflict (23.03 ms) was significantly greater than visual conflict (5.97 ms), $t(33) = 2.26$, $p = 0.031$, Cohen's $d = 0.39$, 95% CI = [1.67, 32.44]. These results show visual dominance at the preresponse level and auditory dominance at the response level.

Furthermore, independent samples t-tests comparing visual and auditory conflict between Experiment 1c and Experiment 2 at both preresponse and response levels revealed no significant differences, ts < 1. These results indicate that when visual stimuli are presented as words, the pattern of response-level sensory dominance remains unchanged, suggesting that visual stimulus presentation modality does not affect response-level sensory dominance.

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4. Experiment 3: Causal Verification of Object Category Influence on Response-Level Sensory Dominance

Experiment 3 used tDCS to causally verify the influence of object categories on response-level sensory dominance. Previous studies have shown that the left anterior temporal lobe is a critical brain region for object category processing (Binney et al., 2018; Diez et al., 2017). Therefore, Experiment 3 applied cathodal stimulation to the left anterior temporal lobe based on Experiment 1c to observe behavioral outcomes. It was hypothesized that inhibiting object category processing would not affect the preresponse level but would alter sensory dominance at the response level.

Experiment 3 recruited 20 university students (9 male, 11 female, mean age 21.50 years, SD = 2.63). All had normal or corrected-to-normal vision, were unaware of the experimental purpose, right-handed, signed informed consent, and received compensation afterward. The study followed the Declaration of Helsinki and was approved by ×× University.

The apparatus included a TES2001 tDCS device from SOTERIX Medical. Stimulation electrodes were wrapped in 5 × 7 cm (35 cm^2) sponge pads. Current was 2 mA (density: 0.06 mA/cm^2). Following international EEG 10-20 system standards and corresponding fMRI research, electrode caps were used for positioning. For the left anterior temporal lobe, the cathode was placed between T7 and FT7, and the anode on the contralateral supraorbital region—standard positions for tDCS studies targeting the left anterior temporal cortex (Akbiyik et al., 2020; Binney et al., 2018). Real stimulation was 2 mA for 10 minutes with 30-second fade-in/fade-out; sham stimulation was 2 mA for 30 seconds with identical fade-in/fade-out.

Other apparatus and materials were identical to Experiment 1c.

4.1.3 Experimental Design and Procedure Participants received 10 minutes of weak electrical stimulation before the experiment. The remaining procedure was identical to Experiment 1c. Participants were randomly assigned to different stimulation groups and completed two tDCS sessions on different days in counterbalanced order.

Data analysis followed the same method as Experiment 1c.

4.2 Results Under sham stimulation (Figure 3C), at the preresponse level, visual conflict (56.75 ms) was significantly greater than auditory conflict (1.62 ms), $t(19) = 4.34$, $p < 0.001$, Cohen's $d = 0.97$, 95% CI = [28.56, 81.71]. At the response level, auditory conflict (68.85 ms) was significantly greater than visual conflict (45.70 ms), t(19) = 2.13, $p = 0.047$, Cohen's d = 0.48, 95% CI = [0.39, 45.91]. These results replicate Experiment 1c, showing visual dominance at the preresponse level and auditory dominance at the response level.

Under cathodal stimulation (Figure 3D), at the preresponse level, visual conflict (54.87 ms) was significantly greater than auditory conflict (29.16 ms), t(19) = 2.66, $p = 0.015$, Cohen's d = 0.60, 95% CI = [5.48, 45.94]. At the response level, no significant difference existed between visual and auditory conflict, $t < 1$. These results indicate that after cathodal stimulation, the preresponse level still showed visual dominance, while sensory dominance at the response level changed.

To further investigate whether cathodal stimulation altered the magnitude of sensory dominance at the preresponse level, Experiment 3 compared sensory dominance indices between sham and cathodal conditions. No significant difference was found at the preresponse level, t(19) = 1.84, $p = 0.082$, indicating that cathodal stimulation did not change the magnitude of visual dominance. These results demonstrate that after cathodal tDCS over the left anterior temporal lobe, visual dominance at the preresponse level remained unaffected, while auditory dominance at the response level disappeared.

[Figure 3: see original paper] Panel A shows the left anterior temporal lobe location according to international EEG 10-20 standards, between T7 and FT7. Panel B shows the HD-explore software simulation of the electric field model for left anterior temporal lobe stimulation on a standard brain model. Panel C shows results under sham stimulation; Panel D shows results under cathodal stimulation. Note: **$p < 0.001$, $p < 0.05$, Bonferroni corrected. Error bars represent standard errors.

5. General Discussion

This study used a 2-1 mapping paradigm across three experiments to investigate how object categories influence response-level sensory dominance. First, Experiment 1 found that object category differences modulate response-level sensory dominance: when category differences were small (Experiment 1a), visual dominance emerged at the response level; when moderate (Experiment 1b), no sensory dominance was observed; and when large (Experiment 1c), auditory dominance emerged. Moreover, Experiment 2 changed visual stimulus presentation modality from Experiment 1c and found similar response-level sensory dominance patterns, indicating that the effect is independent of presentation modality. Experiment 3 applied cathodal tDCS to the left anterior temporal lobe—a critical region for object category processing—and found that response-level sensory dominance disappeared, further validating the causal influence of object categories on response-level sensory dominance.

This study found visual dominance at the preresponse level, consistent with previous research (Chen & Zhou, 2013; Koppen et al., 2009), possibly reflecting audiovisual asymmetry in early processing stages. Previous studies have found that visual distractors produce significantly stronger interference than auditory distractors in cross-modal conflict (Kang & Luo, 2020; Donohue et al., 2013). Attentional orienting theory suggests that compared to automatically processed auditory stimuli, visual stimuli require more attentional resources and lower vigilance (Dietze & Poth, 2023). In this study, visual and auditory stimuli were input simultaneously. At the preresponse level, information processing includes perceptual and semantic levels. Auditory stimuli were processed automatically, occupying fewer attentional resources, while visual stimuli consumed substantial attentional resources, leading to prioritized visual processing.

This study demonstrates that intermediate processing levels regulate response-level sensory dominance. When category differences are large, auditory dominance emerges at the response level; when small, visual dominance emerges. The spreading priming model (Schubert, 2021) may explain this: visual distractors activate additional irrelevant semantic representations that interfere with auditory target judgments, particularly when semantic relevance is strong, activating more extra semantic representations and producing stronger conflict effects. Our findings also align with evolutionary perspectives suggesting that attentional resource allocation is influenced by organisms' current needs, with individuals making adaptive trade-offs based on environmental cues, such as avoiding danger and selective cognitive coordination (Haselton & Buss, 2000). When a snake is camouflaged in grass, it becomes easier to detect if it makes a sound. In the current study, when cross-modal object category differences are large, more accurate discrimination can be achieved through the auditory channel.

Our findings differ from Chen and Zhou (2013), which used faces and names of political figures and celebrities and found visual dominance at the preresponse level and auditory dominance at the response level. Experiment 1c (large category differences) replicated their results, possibly because faces are special (Martin & Chao, 2001; Ubaldi & Fairhall, 2021). Political figures and celebrities belong to distinct social categories that, despite sharing many features (e.g., two eyes, one nose), can be quickly distinguished through long-term learning. Researchers have even identified a unique high-dimensional personal information space dedicated to storing individual information (e.g., traits, attitudes, status) (Castello et al., 2021).

Although Experiment 1 showed that object categories influence response-level sensory dominance, bottom-up stimulus presentation modality could not be excluded. In Experiment 1, visual stimuli were pictures while auditory stimuli were object names. Pictures access perceptual representations earlier, while spoken words access semantic representations earlier (Baddeley & Hitch, 2017; Potter & Fox, 2009; Wiggett et al., 2009). Processing speed mismatches might have affected results. Previous research shows that for pictures, understanding meaning occurs earlier than understanding name codes, whereas for words, the opposite pattern occurs (Dirani & Pylkkänen, 2023). In classification tasks, pictures are typically classified faster than words (Dirani & Pylkkänen, 2023), while in naming tasks, words are named faster than pictures (Nieznański, 2020). However, although processing times may differ across modalities, category representation processing is completed before the response level. Therefore, object category presentation modality should not affect response-level sensory dominance, a hypothesis supported by Experiment 2's results.

Finally, this study applied sham and cathodal tDCS to the left anterior temporal lobe (Akbiyik et al., 2020; Binney et al., 2016; Mesulam et al., 2013). The left anterior temporal lobe has been extensively shown to play a crucial role in object naming and recognition. Damage to this region in semantic dementia patients leads to impaired conceptual knowledge, causing generalization errors (Lambon Ralph & Patterson, 2008) and semantic-association-based memory illusions (Binney et al., 2018; Diez et al., 2017). This study found that regardless of sham or cathodal stimulation, the preresponse level maintained stable visual dominance unaffected by tDCS, while cathodal stimulation altered response-level sensory dominance, providing causal evidence for object categories' influence on response-level sensory dominance.

This study is the first to observe that intermediate processing levels regulate response-level sensory dominance by manipulating object category differences. Although research has shown that sensory dominance manifests differently across processing levels—visual dominance at early perceptual levels and auditory dominance at late response levels (Chen & Zhou, 2013; Li et al., 2019)—intermediate processing levels responsible for internal representations such as thought and semantics (Chen et al., 2010; Velasquez et al., 2021) play important roles in higher cognition and social interaction. However, researchers know little about intermediate processing levels' role in multisensory integration. This study used object categories as an internal representation to investigate how intermediate processing levels influence sensory dominance, refining the processing level hypothesis: early perceptual processing shows visual dominance, while sensory dominance at late response levels is flexibly regulated by intermediate processing levels, with different internal representations producing different response-level outputs. Future research on multisensory integration should consider intermediate processing levels responsible for internal representation.

By manipulating object category differences, intermediate processing levels can regulate response-level sensory dominance: small category differences produce visual dominance, while large differences produce auditory dominance. This behavioral pattern is independent of visual stimulus presentation modality but is top-down regulated by the left anterior temporal lobe.

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Abstract (English)

The sensory dominance is a phenomenon in which the brain selectively processes specific sensory information when presented with multisensory inputs, thereby enhancing human perception of external stimuli. Previous studies have discussed the sensory dominance at perceptual and response levels. However, how the intermediate processing level between perceptual and response levels affects the sensory dominance remains unknown. Therefore, the present study adopted the cross-modal 2-1 mapping paradigm and manipulated object categories through three studies to investigate the role of the intermediate processing level on sensory dominance in cross-modal conflict.

In this paradigm, based on key mapping, cognitive processing levels can be defined into preresponse level (included perceptual and semantic levels) and response level. The difference between the audiovisual incongruent condition and the audiovisual congruent condition was called the conflict effect, and the sensory dominance can be obtained by comparing the conflict effect of attention to vision and auditory. Experiment 1 manipulated the degree of difference in object categories to explore its impact on sensory dominance. Experiments 1a~c involved animal objects (small differences), tool objects (moderate differences), and animal and musical instrument objects (large differences), 30 participants were recruited for each experiment. Because visual pictures reach perceptual representation earlier, while auditory sounds reach semantic representation earlier.

Therefore, Experiment 2 (34 participants) changed visual pictures into visual words on the basis of Experiment 1c to explore effects of visual presentation way of object categories on sensory dominance. In Experiment 3 (20 participants), transcranial direct current stimulation (tDCS) was used on the left anterior temporal lobe, an important brain region responsible for processing object categories to further causally study effects of object category on the sensory dominance of the response level.

The results of Experiment 1 showed that, no matter what the difference of object categories, at the preresponse level, the conflict effect of attention to auditory was significantly greater than that of attention to vision, that is, visual dominance. However, at the response level, visual dominance appeared when the object category difference was small (Experiment 1a), no sensory dominance was observed when the object category difference was moderate (Experiment 1b), auditory dominance appeared when the object category difference was large (Experiment 1c). It was found that the results of Experiment 2 and Experiment 1c were consistent, that is, auditory dominance, indicating that this behavior pattern was not affected by the bottom-up visual presentation way. The results of Experiment 3 showed that under cathodal tDCS condition, the preresponse level still showed visual dominance, but the response level no longer showed sensory dominance. This result showed that effects of object categories on the sensory dominance of the response level from the causal level.

The mechanism of sensory dominance is still under investigation. The present study was first to find that object categories affected the sensory dominance of the response level. From the perspective of cognitive processing level, intermediate processing level played a regulating role in the sensory dominance of the response level, enriching the explanatory theory of sensory dominance and providing a new perspective for the study of sensory dominance in cross-modal conflict.

Keywords: object categories, visual dominance, auditory dominance, preresponse level, response level

Note: Figure translations are in progress. See original paper for figures.