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The process of object individuation shared across visual and tactile modalities

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ABSTRACT

Distinguishing objects from the background, a process known as Object Individuation (OI), is fundamental for us to interact with the environment and relies critically on location information across sensory modalities. Nonetheless, it remains unclear and contested in the literature whether the enumeration of tactile and visual events relies on the OI process (especially given spatial constraints), or if the representation of numerosity is governed by a modality-independent mechanism common to both visual and tactile systems. In this study, we used a cross-modal enumeration and a working memory dual-task paradigm to investigate whether OI processes in tactile and visual modalities draw upon a shared cognitive resource.

We implemented two experiments. In Experiment 1, we combined a tactile working memory (WM) task with visual enumeration, and in Experiment 2, we used a visual WM task with tactile enumeration. Both experiments revealed that the task-irrelevant WM load significantly modulated subitizing performance (enumeration of small quantities) in the target modality. Under high WM load, participants showed increased error rates and reduced subitizing capacity compared to low load. This modulation is selective to the subitizing range and cannot be attributed to general dual-task costs, ruling out general dual-tasking effects. The data shows that visual and tactile working memory and enumeration ("subitizing") share a common OI process that operates on location, independent of the sensory modality. This finding is consistent with existent neuroimaging evidence that highlights the modality-shared role of frontoparietal brain regions (e.g., IPS, LPFC) in enumeration and working memory.

1. Introduction

In a pioneering 1871 self-experiment, William Stanley Jevons demonstrated a sharp cognitive boundary in numerical perception: the instant, flawless apprehension of up to four items—later termed "subitizing"—versus error-prone estimation for larger quantities (Jevons, 1871). This seminal work established that the human mind possesses strict capacity limits when parsing the environment into discrete units, a cognitive process known as object individuation. The architectural basis for this limitation can be understood through Atkinson and Shiffrin's (1968) "general theory" of human memory. Their multi-store model posits that while environmental stimuli

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initially enter distinct, modality-specific sensory registers (such as visual or tactile stores), active control processes transfer a selected subset of this information into a central, amodal short-term store (Atkinson & Shiffrin, 1968).

This central workspace—now widely conceptualized as working memory—imposes profound constraints on numerical cognition. Because working memory capacity is strictly bounded, the cognitive mechanism responsible for active object individuation is similarly capped. When the number of targets exceeds this shared limit of three to four items, precise individuation fails, forcing the system to rely on approximate estimation strategies.

This architectural bottleneck forms the primary motivation for the current research: if object individuation is constrained by a central, amodal working memory system rather than peripheral sensory organs, then the capacity limits of exact enumeration should be consistent regardless of how the stimuli are perceived. To test this hypothesis, this study investigates whether the fundamental mechanisms of object individuation are truly shared across visual and tactile modalities.

Indeed, research in numerical cognition is now increasingly exploring the intricate relationship between sensory modalities, enumeration processes, and working memory, often suggesting an embodied foundation for abstract number concepts. Embodied numerical cognition theory suggests that the meaning of numbers is deeply grounded in sensorimotor experiences, such as interactions with fingers and space, and that numerical proficiency emerges from grounding core concepts like magnitude, ordinality, and cardinality (Anobile et al., 2021; Sixtus et al., 2023). A core debate concerns the mechanism for enumeration of small quantities, known as subitizing, which is often contrasted with the Approximate Number System (ANS) used for larger estimates (Cai et al., 2021). Proposed mechanisms for subitizing include both domain-general processes, like attention, and domain-specific mechanisms, like pattern recognition, making it necessary to integrate studies across visual, tactile, and auditory modalities to resolve the controversy (Katzin et al., 2019).

A key process underlying number sensing is object individuation, which entails distinguishing objects from the background or from each other, and this process is constrained by spatial features of the stimuli, as well as closely related to the individual working memory (WM) capacity (Auvray et al., 2011; Feldman & Tremoulet, 2006; Katus & Eimer, 2018, 2019; Morimoto, 2020; Piazza et al., 2011; Salmela et al., 2014; Tian & Chen, 2018; Ziegler & Drewing, 2022). The most prominent characteristic of working memory is its capacity limitation, typically holding only 3 to 4 objects (Baddeley, 2012; Cowan, 2010; Katus & Eimer, 2018).

Here, the neural and cognitive mechanisms underlying the retention of number estimates in working memory (WM) remain a key area of investigation, with the ANS involving a right-lateralized frontoparietal network, and vibrotactile studies pointing to the lateral prefrontal cortex (LPFC) for maintaining magnitudes (Uluc et al., 2020).

Historically, several classical theories have been proposed to explain how limited cognitive resources constrain performance across competing tasks, such as enumeration and working memory. According to the Multi-Component Model (Baddeley & Hitch, 1974) and the Controlled Attention View (Kane et al., 2001), enumeration performance is limited by the central executive's ability to manage these dual demands. When a participant enumerates a large set of items, they must engage in a constant processing-storage trade-off. As the number of items increases, the “processing” demand of identifying and tracking which items have already been counted consumes a larger share of the common resource pool. This diversion of attentional energy away from the “storage” of the current count leads to a reduction in recall accuracy, illustrating that enumeration could be fundamentally constrained by the individual's total WM capacity (Daneman & Carpenter, 1980; Engle et al., 1999; Daneman and Tardif, 1987; Towse, Hitch and Hutton, 2000).

This relationship is further refined by the Time-Based Resource-Sharing (TBRS) Model, which highlights the role of temporal decay and the central bottleneck. During enumeration, the act of identifying an object constitutes a retrieval or processing step that momentarily blocks the “attentional spotlight” from refreshing the mental representation of the current count. Because the cognitive load of enumeration is determined by the ratio of these identification demands to the time available, a faster or more complex visual array increases the cognitive load. This reduces the opportunities for rapid attention switching, allowing the memory trace of the count to decay. Consequently, enumeration performance drops when the pace of processing exceeds the system's ability to switch back and refresh the stored total (Barrouillet et al., 2004).

In addition, the Task-Switching Model suggests that enumeration performance is primarily a function of the time spent away from maintenance. In this view, the limitation is not a shared “energy” but rather the duration of the intervals during which the participant is focused on scanning the environment instead of rehearsing the count. Whether one views the limit as a shared resource or a temporal decay process, it is clear that enumeration serves as a “complex span” task in its own right. Effective performance requires a balance where the difficulty of the visual processing does not overwhelm the system's inhibitory control, ensuring that the central executive can maintain the “purity” of the count without succumbing to the interference of the background task (Towse & Hitch, 1995; Turner & Engle, 1989).

Given the relatively solid evidence from visual modality, however, it seemed surprising that there is little evidence from the tactile domain and cross-modal domain (e.g., visual and tactile modalities) to show the relationship between individual's working memory capacity and enumeration performance. To address this issue, researchers have employed a cross-modal dual-task paradigm to investigate whether working memory capacity is shared across or independent between modalities. In their experiments, participants are required to simultaneously remember stimulus sets from different modalities (e.g., visual and haptic, or visual and auditory). The performance of one modality's WM task is then observed while manipulating the WM load of the other modality. Many dual-task experiments have reported a cross-modal interference effect, where an increase in the WM load of one modality leads to a decline in the WM performance of the other modality (Cowan et al., 2014; Fougnie et al., 2018; Salmela et al., 2014).

However, even the interpretation of the cross-modal interference effect remains controversial. Some researchers regard the cross-modal interference effect as strong evidence for the existence of a shared, cross-modal working memory storage system (Cowan, 2010, 2011). In contrast, others argue that the interference observed in cross-modal WM tasks is likely caused by general dual-task coordination costs (Cocchini et al., 2002), rather than a cognitive bottleneck in the storage component of the WM task. Moreover, the exact

relationship between enumeration performance and working memory capacity has been largely uncharted. Therefore, resolving this controversy necessitates further research to demonstrate the task-specificity of the interference effect observed in cross-modal working memory tasks.

While seminal work has suggested that the brain recruits "visual" spatial hardware for tactile tasks in the absence of sight (Sadato et al., 1996; Sadato et al., 1998; Sadato et al., 2002), the specific constraints of the tactile system itself remain under-explored. Notably, existing research on tactile enumeration and subitizing has predominantly focused on stimuli presented across multiple fingers or broad body surfaces (Gallace et al., 2008; Plaisier et al., 2009; Riggs et al., 2006; Ziegler, Stricker and Drewing, 2023). This focus potentially limits our understanding of numerical mechanisms by overlooking the unique physiological properties of small, high-acuity surfaces. Given the dense concentration of Merkel cells and the high spatial resolution of the fingertips (Johnson & Phillips, 1981; Van Boven & Johnson, 1994), enumeration within a single fingertip likely utilizes a differential processing pattern compared to the rest of the body (Auvray et al., 2011; Ziegler & Drewing, 2022). Furthermore, as tactile short-term memory is closely tied to the recruitment of primary somatosensory areas (Katus et al., 2015), investigating *intradigital subitizing* provides a critical opportunity to examine how limited spatial resources and working memory capacity interact to facilitate object individuation. By targeting tactile enumeration on this micro-scale, the present study aims to bridge the gap between sensory-specific constraints and the broader modality-independent mechanisms of numerosity.

This consideration hence provides a rationale for the experimental design of the present study. Here, we raised some empirical questions: When executing cross-modal dual-tasks composed of these tasks (e.g., tactile subitizing and visual working memory, or visual subitizing and tactile working memory), will subitizing performance be modulated by the load of the simultaneously-occurring cross-modal working memory task, similar to within-modal visual dual-tasks? Additionally, is this modulation task-specific? In other words, is this modulation due to competition for object individuation resources rather than a generalized cost of cross-modal dual-task coordination?

Object individuation is closely related to — and in some formulations overlaps with — attentional indexing (Pylyshyn, 1989; Trick & Pylyshyn, 1994) and location-based object selection (Kahneman et al., 1992; Xu & Chun, 2009), all of which are capacity-limited operations defined over spatial location. We therefore frame the present study as testing whether enumeration and working memory draw on a shared location-based individuation resource, while remaining agnostic as to which of these closely related constructs best characterizes it.

To address these questions, we designed two cross-modal dual-task experiments to investigate the visual-tactile shared object individuation process by integrating object individuation tasks of different modalities within a single framework. In Experiment 1, we used a dual-task paradigm consisting of a tactile working memory task and a visual enumeration task to explore the modulation of tactile working memory load on visual subitizing performance. A visual enumeration task was used as a control to exclude the potential explanation of the results by cross-modal dual-task coordination costs. In Experiment 2, we reversed the task modalities, using a dual-task paradigm composed of a visual working memory task and a tactile enumeration task to investigate the modulation of visual working memory load on tactile subitizing performance.

We hypothesize that the object individuation resource is shared across modalities and is independent of the stimulus modality and task format. Therefore, we predict that, similar to within-modal dual-task results, subitizing performance will be modulated by cross-modal working memory load; specifically, the error rate of subitizing will be lower and precision higher under low working memory load compared to high working memory load. On the contrary, if this modulatory effect is not expected to be present in the cross-modal estimation and working memory tasks, which would further indicate that the cross-modal working memory and subitizing tasks share a distinct object individuation resource.

1.1. Experiment 1: modulation of visual subitizing performance by tactile working memory load

Experiment 1 was designed to investigate the potential cross-modal shared nature of the object individuation resource by examining how tactile spatial working memory load modulates visual subitizing performance. Experiment 1 included a dual-task involving enumeration and working memory, as well as two single-tasks: the visual enumeration single-task and the tactile working memory single-task. Similarly, because the visual enumeration task is influenced throughout its duration by the tactile working memory task, while the working memory task is only influenced by the enumeration task during part of its maintenance phase, we focused primarily on the results of the enumeration task.

We hypothesize that visual subitizing and tactile working memory share the object individuation resource, leading to resource competition when performed simultaneously. Specifically, compared to the low working memory load condition, when the working memory task consumes a greater amount of the object individuation resource, there will be a more significant reduction in subitizing capacity, an increase in error rate, and a decrease in precision. Conversely, we hypothesize that working memory load will not modulate the performance of estimation, which is based on the Approximate Number System (ANS).

2. Method

2.1. Participants

A total of 26 undergraduate student volunteers were recruited for this experiment, including 14 males. The mean age of the participants was 21 $\pm$ 0.34 years, and all were right-handed. Data from one participant were excluded due to enumeration task results falling outside three standard deviations, resulting in a final effective sample size of 25, which meets the minimum effective sample

size estimate derived from G*Power ($N = 16$). All participants reported normal tactile sensation, normal or corrected-to-normal visual acuity, and no known neurological disorders. All participants provided written informed consent prior to the experiment and received compensation upon completion. The study protocol was approved by the Academic Affairs Committee of the School of Psychological and Cognitive Sciences at Peking University (Approval No. #2021-10-18).

2.2. Experimental design and procedure

Each participant was required to complete three tasks: one visual enumeration and tactile working memory dual-task, and two single-tasks (visual enumeration single-task and tactile working memory single-task). The single-tasks served as baseline conditions to control for potential confounding effects of physical stimulus differences. The experiment was conducted over two days. Since the dual-task was lengthy, the two single-tasks were completed on the same day. The order of the dual-task and single-tasks, as well as the order of the two single-tasks, were counterbalanced across participants.

The physical stimuli were identical across the single- and dual-tasks. The key difference was in the response modes for the dual-task, where participants were required to sequentially report two items: the number of stimulus dots presented in the enumeration task and whether the position of the probe dot in the working memory task had been presented during the memory phase (Old/New judgment). In the single-tasks, participants answered only one item after stimulus presentation: the numerosity for the enumeration single-task, and the stimulus dot position for the working memory single-task (Fig. 1).

The experimental procedure, using the dual-task as an example (see Fig. 1 for details) is as follows: Each trial began with a fixation point presented on the screen for 500–1000 ms. 500 ms after the fixation point disappeared, the tactile stimulus dots were presented. These dots served as the sample stimuli for the working memory task, and participants were required to memorize their locations. The stimulus duration was 2000 ms, with a presentation frequency of 8 Hz. Approximately 150–1550 ms (labeled as T1) after the stimulus disappeared, an auditory cue (70 Hz, 50 ms) was presented to signal the imminent presentation of the visual enumeration stimuli.

The visual enumeration stimuli consisted of small black and white squares, all presented within a $10^\circ \times 10^\circ$ rectangular area on a grey background. The parameters of the squares were set based on previous literature on single numerosity enumeration tasks (Anobile et al., 2012; Burr et al., 2010). The size of the stimulus squares was constant with a side length of 1.2°, and their positions were randomized (the control method for continuous quantity factors was adapted from Burr et al., 2010), with a minimum separation distance of 2° between any two squares. Throughout the experiment, the total luminance of the black and white squares was equal to the luminance of the grey background (to prevent luminance differences from interfering with numerosity processing). The visual stimuli were presented for 50 ms, followed by a black-and-white random dot pattern serving as a masking stimulus (Anobile et al., 2012; Burr et al., 2010), presented for 150 ms. The blank screen duration after the mask disappeared ranged from 1550 to 150 ms ("T2"). The sum of T1 and T2 was fixed at 1700 ms, ensuring a working memory maintenance duration of 3000 ms in every trial. In the subsequent test phase, a probe dot was presented again at 8 Hz for 2000 ms. Finally, the response screen appeared, where participants sequentially responded to two tasks: the number of stimulus dots and whether the probe dot position was 'Old' or 'New'. The working memory task had two load levels: low load (memorizing the positions of 2 stimulus dots) and high load (memorizing the positions of 4 stimulus dots). Additionally, 1 and 3 dots were included as filler stimuli and were excluded from subsequent analysis. The numerosity task was divided into eight levels: 1 to 8. Each task comprised 320 formal trials ($2 \times 8 \times 20$) and 32 ($2 \times 8 \times 2$) filler trials. Before the formal experiment, participants completed 20 practice trials with feedback.

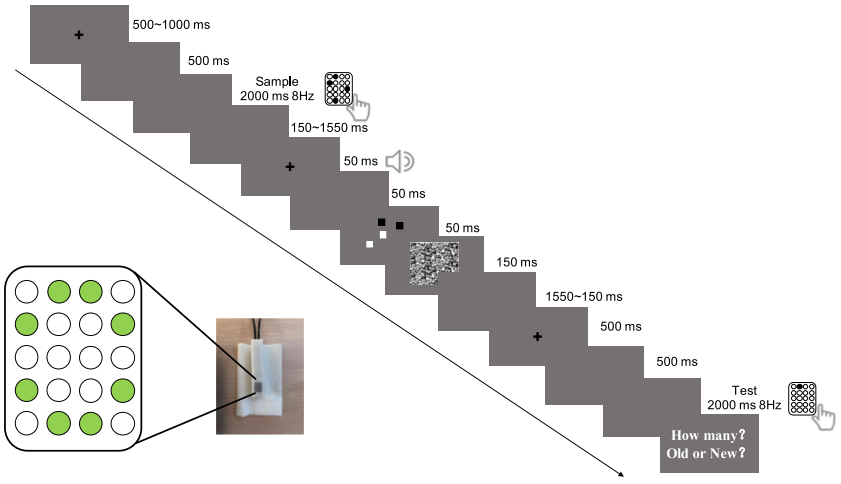

Fig. 1. A schema for Dual-task in Experiment 1. The magnified view of the tactile stimulus display is in the bottom left corner. The sample and test stimuli are both presented at the "green" locations. The colors are only used for differentiation during presentation; there are no color markings on the actual experiment screen or on the tactile display.

2.3. Data analysis

We focused on the enumeration task results, specifically with data for set sizes 2 through 7. First, subitizing capacity was calculated based on the Error Rate (ERR) results. Second, the ERR, Weber Fraction (WF), and Coefficient of Variation (CV) were analyzed across the different load conditions (The analyses of WF, CV were referred to *Supplementary materials S1: additional analysis for Experiment 1*). Because ERR treats all errors equally regardless of magnitude (e.g., a one-unit versus a five-unit error), it can obscure subtle effects, particularly within the subitizing range. To better account for error magnitude, we analyzed response precision using the coefficient of variation (CV = standard deviation / numerosity). However, because potential strong accuracy biases could limit the CV's reliability for measuring sensory accuracy, we also report the Weber fraction (WF = standard deviation / mean response) to provide a bias-free measure of sensory precision. The calculations for CV and WF are detailed in Eqs. (1) and (2) below.

(*n*: numerosity level; *K:* the total number of trials of the particular numerosity level *n;* $R_{n,j}$: participants' response at a particular trial j (from 1 to K) at the numerosity level *n*):

$$CV(n) = \frac{\sqrt[2]{\frac{1}{K}\sum_{j=1}^{K}\left(R_{n,j} - \frac{1}{K}\sum_{j=1}^{K}R_{n,j}\right)^2}}{n} \tag{1}$$

$$WF(n) = \frac{\sqrt[2]{\frac{1}{K}\sum_{j=1}^{K}\left(R_{n,j} - \frac{1}{K}\sum_{j=1}^{K}R_{n,j}\right)^2}}{\left(\frac{1}{K}\sum_{j=1}^{K}R_{n,j}\right)} \tag{2}$$

CV and WF were first calculated at each numerosity level (1–8), and then averaged them at 2, 3,4 and 5, 6, 7 for subitizing range and estimation range respectively (Lou et al., 2023).

Finally, to rule out the influence of physical differences between the working memory load conditions on the dual-task results, analyses were performed on the single enumeration task performance, as well as on difference scores (Delta Error) and ratio scores (Weber Ratio and CV Ratio) obtained by using the single enumeration performance as a baseline against the dual-task results (the analyses were found in supplementary materials S1).

3. Results

Recent research on visual enumeration suggests that sigmoid function fitting is an efficient method for determining the subitizing range (Anobile et al., 2019; Piazza et al., 2011). In the present study, we similarly applied sigmoid function fitting to define the tactile subitizing range based on its inflection point. This inflection point was identified as the point at which the second derivative of the sigmoid function equals zero.

Sigmoid functions were fitted to the participants' enumeration Error Rates (ERR) under the single-task (denoted as no_load), dual-task low-load (low_load), and dual-task high-load (high_load) conditions. This allowed for the calculation of subitizing capacity for

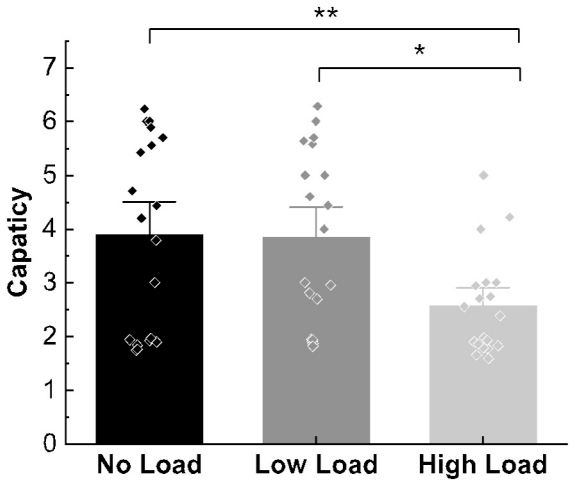

Fig. 2. Capacity of numerosity perception under different working memory loads in Experiment 1. The bar charts represent group mean data, the diamonds represent individual subject data, and the error bars indicate the standard error. Asterisks represent significance, where *$p < .05$, **$p < .01$, and ***$p < .001$.

each participant under the three conditions. Statistical analysis was performed on the data from the 19 participants whose goodness-of-fit (R^2) was greater than 0.6, this means that a participant was retained only if the goodness of fit of the sigmoid model exceeded $R^2 = 0.60$ in every condition of both the single-task and dual-task blocks; anyone failing this requirement in any condition of either block was excluded (see ***Supplementary material S4*: Sigmoid-Fitting Procedure, Participant Exclusion Criterion, and Sensitivity Analyses)**. The results (see Fig. 2) showed a significant main effect of load level ($F(2,36) = 5.759$, $p = .007$, η_p^2=0.242). Post-hoc analysis revealed that the subitizing capacity in the no_load condition (M = 3.893, SE = 0.409) was significantly higher than in the high_load condition ($t(18) = 3.426$, $p = .009$, Cohen's d = 0.964; M = 2.572, SE = 0.219). Similarly, the subitizing capacity in the low_load condition (M = 3.854, SE = 0.369) was also significantly higher than in the high_load condition ($t(18) = 2.949$, $p = .026$, Cohen's d = 0.998) (See Fig. 2).

3.1. Dual-task error rate analysis

We conducted a 2 (Working Memory Load) × 6 (Enumeration Set Size) repeated-measures ANOVA. The results revealed a significant interaction between Working Memory Load and Enumeration Set Size ($F(5,120) = 3.180$, $p = .010$, η_p^2=0.117), indicating that the effect of high vs. low load on enumeration performance varied across different set sizes (see Figs. 3 and 4). Simple effects analysis showed that when the enumeration set size was 2 ($F(1,24) = 16.56$, $p < .001$,η_p^2=0.421), the participants' enumeration error rate was significantly higher in the high-load condition (M = 0.174, SE = 0.034) compared to the low-load condition (M = 0.096,SE = 0.021), $t(24) = 4.07$, $p = .0004$, Cohen's d = 0.814.

A similar significant difference in error rate between the high-load (M = 0.286, SE = 0.045) and low-load (M = 0.218, SE = 0.044) conditions was observed for set size 3 ($F(1,24) = 6.78$, $p = .016$,η_p^2=0.231), $t(24) = 2.60$, $p = .0156$, Cohen's d = 0.521.

However, this difference between high and low load has not been observed for the relatively larger set sizes of 4 to 7 (ps > 0.05). The modulatory effect was confined to the small number range, suggesting that working memory load only modulates subitizing performance and does not significantly impact estimation performance based on the Approximate Number System (ANS). This is consistent with our prediction, providing preliminary evidence that visual subitizing and tactile working memory share the object individuation resource. Furthermore, the repeated-measures ANOVA revealed a significant main effect of Working Memory Load ($F(1,24) = 7.90$, $p = .010$, η_p^2=0.248); the enumeration error rate was lower in the low-load condition (M = 0.404, SE = 0.035) compared to the high-load condition (M = 0.435, SE = 0.035), $t(24) = -4.230$, $p = .0003$, Cohen's d = .-846. A significant main effect of

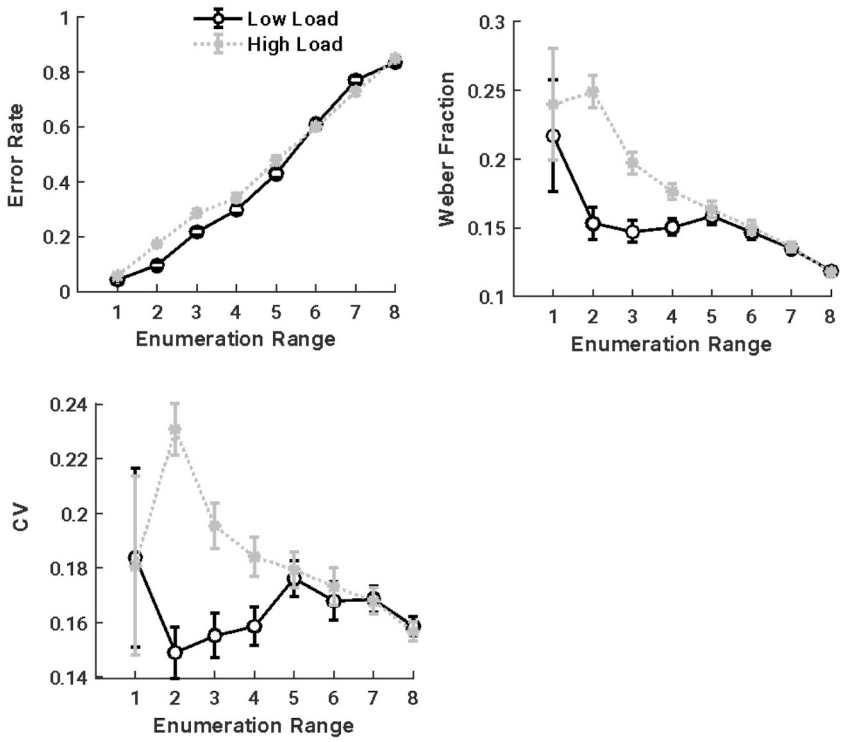

Fig. 3. Results for the numerosity enumeration task in the dual-task paradigm for Experiment 1. The black line represents the low-load condition, under which subjects were required to maintain memory for two tactile stimulus locations while completing the visual enumeration task. The grey line represents the high-load condition, under which subjects were required to maintain memory for four tactile stimulus locations while completing the enumeration task. Error bars indicate the standard error.

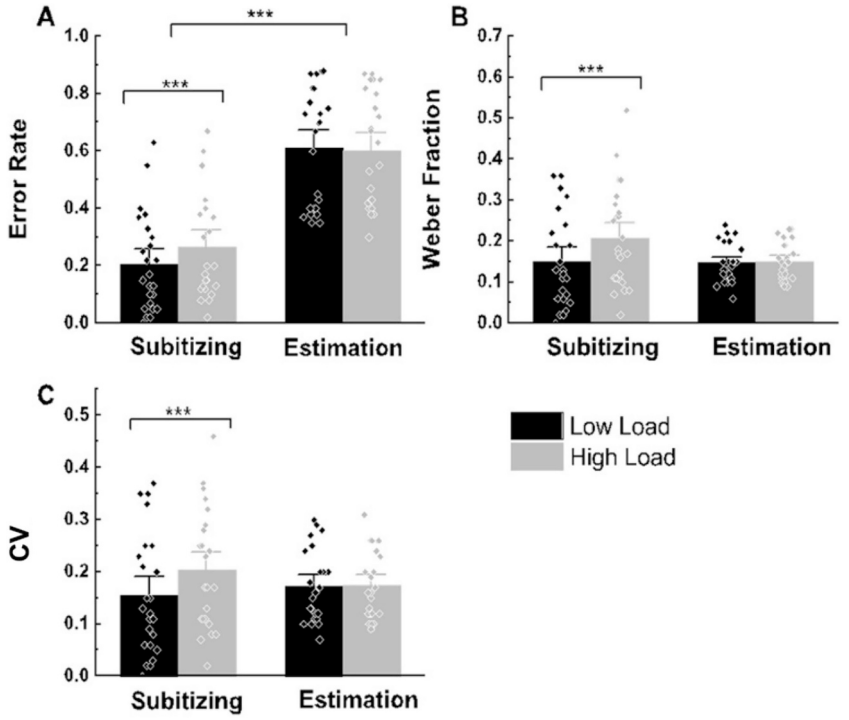

Fig. 4. Bar plots of the numerosity enumeration task in the dual-task paradigm for Experiment 1. The bar charts represent group mean data, the diamonds represent individual subject data, and the error bars indicate the standard error. Asterisks represent significance, where *$p < .05$, **$p < .01$, and ***$p < .001$.

Enumeration Set Size was also found ($F(5,120) = 128.445$, $p < .001$,η_p^2=0.843); the error rate increased as the set size increased. Post-hoc tests showed significant differences between all set sizes ($ps < 0.01$).

Additional analyses further validated the differential modulation of tactile working memory (WM) load on visual enumeration by categorizing the data into subitizing (2–4) and estimation (5–7) ranges. Dual-task results revealed a significant interaction between WM Load and Number Range across error rates ($F(1,24) = 9.287$, $p = .006$, $\eta_p^2 = 0.279$), Weber Fraction ($F(1,24) = 30.835$, $p < .001$, η_p^2=0.562), and Coefficient of Variation ($F(1,24) = 27.079$, $p < .001$, $\eta_p^2 = 0.530$). Specifically, high tactile load significantly impaired both accuracy and precision within the subitizing range (all $ps < 0.001$), while leaving the estimation range unaffected ($ps > 0.05$). After subtracting single-task baselines, the Delta Error still showed a significant interaction ($F(1,24) = 4.096$, $p = .054$, $\eta_p^2 = 0.146$), with a much larger load effect in the subitizing range ($F(1,24) = 28.16$, $p < .001$, $\eta_p^2 = 0.533$). These findings rule out physical stimulus differences and reinforce the conclusion that subitizing and tactile working memory share limited cognitive resources (see ***Supplementary materials S1*: additional analysis for Experiment 1**).

4. Discussion

The cross-modal dual-task results in Experiment 1 revealed a clear modulation of visual subitizing performance by tactile working memory load. Specifically, compared to the low working memory load, participants exhibited a higher error rate and lower precision in subitizing under high working memory load. The results further indicated a significant reduction in subitizing capacity under the high working memory load condition relative to the low working memory load condition.

Crucially, this modulatory effect was absent during the estimation process. We interpret this finding based on the hypothesis that subitizing, like working memory, relies on the object individuation process. When performed concurrently, these tasks compete for a limited object individuation resource. Consequently, the high working memory load, which consumes more object individuation resources, results in a more severe impairment of subitizing performance. In contrast, estimation relies on the Approximate Number System (ANS), which is not significantly modulated by the consumption of object individuation resources imposed by the working memory task. Therefore, the cross-modal modulation observed in the dual-task is not due to general cross-modal dual-task coordination costs but is caused by the competition for object individuation resources between tactile working memory and visual subitizing.

The dual-task results support our hypothesis that the object individuation resource is shared across the visual and tactile modalities. The single-task analysis showed that when only the physical stimuli of the working memory task were presented without requiring cognitive processing, different working memory loads did not modulate subitizing performance, and there was no significant difference in the overall effect of the physical stimuli across different loads on the enumeration task. This rules out the alternative

explanation that the modulation of subitizing performance by different memory loads was caused by physical stimulus differences between the high and low load conditions. Finally, by using the single-task results as a baseline and calculating difference scores (Delta Error) and ratio scores (Weber Ratio, CV Ratio), as largely bias-free measurements against the dual-task results, we found that the modulatory effect of working memory load on subitizing performance persisted in the Delta Error analysis. However, this load difference disappeared in the precision indicators (Weber Ratio and CV Ratio).

Taken together, results from Experiment 1 provide initial evidence that the object individuation resource is shared across the visual and tactile modalities, demonstrating that a tactile-modal object individuation task can modulate a visual-modal object individuation task. To investigate this issue more systematically and comprehensively, in Experiment 2 we reversed the task modalities to explore the reverse direction of modulation, thereby strengthening the evidence for the cross-modal shared nature of the object individuation resource.

4.1. *Experiment 2: modulation of tactile subitizing performance by visual working memory load*

Experiment 2 was designed to investigate the potential cross-modal shared nature of the object individuation resource by examining how visual spatial working memory load modulates tactile subitizing performance. The experiment similarly included a dual-task combining enumeration and working memory, as well as two single-tasks: a tactile enumeration single-task and a visual working memory single-task. As in Experiment 1, we focused primarily on the results of the enumeration task. In this experiment, we hypothesized that tactile subitizing and visual working memory share the object individuation resource, leading to resource competition when performed simultaneously. Specifically, we expected that compared to the low visual working memory load condition, when the visual working memory task consumes more object individuation resources, there would be a more significant reduction in tactile subitizing capacity, an increase in error rate, and a decrease in precision. Correspondingly, working memory load was not expected to modulate estimation performance based on the ANS.

5. Method

5.1. *Participants*

A total of 24 undergraduate student volunteers were recruited for this experiment, including 11 males. The mean age of the participants was 19.2 $\pm$ 0.83 years, and all were right-handed. This sample size meets the minimum effective sample size estimate based on G*Power ($N = 16$). All participants reported normal tactile sensation, normal or corrected-to-normal visual acuity, and no known neurological disorders. All participants provided informed consent prior to the experiment and received compensation upon completion. The study protocol was approved by the Academic Affairs Committee of the School of Psychological and Cognitive Sciences at Peking University.

5.2. *Experimental design and procedure*

The working memory task required participants to judge whether two or four colored squares, presented sequentially, were the

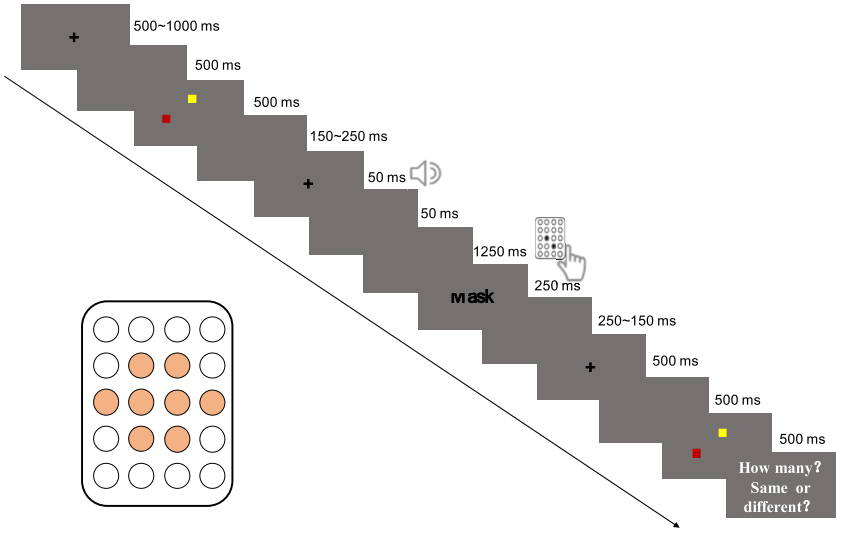

Fig. 5. A schema for Dual-task in Experiment 2. The magnified view of the tactile stimulus display is in the bottom left corner. The orange dots array in the flow chart is presented at the orange location. The colors are only used for differentiation during presentation; there are no color markings on the actual experiment screen or on the stimulus quantity display.

same. The stimulus squares were 1° × 1° in size. The color of each square was selected from a set of 7 highly discriminable colors (red, green, blue, grey, yellow, purple, cyan), and no color was repeated within a single trial. The stimuli were presented for 500 ms, with all squares appearing within a 10° × 10° rectangular area on a grey background. The probe stimulus was presented 3000 ms after the memory stimulus disappeared, maintaining the same number, size, and position as the memory-phase stimuli, and was presented for 500 ms. In half of the trials, the colors of all squares in the probe stimulus remained consistent with the memory phase; in the other half, the color of one square in the probe stimulus changed. Participants were required to press a key to report whether the probe stimulus was the same as the memory stimulus (Fig. 5).

The working memory task had two load levels: low load (memorizing the colors of 2 stimulus squares) and high load (memorizing the colors of 4 stimulus squares). Additionally, 1 and 3 squares were included as filler stimuli and were excluded from subsequent analysis. The numerosity task was divided into eight levels: 1 to 8. Each task included 320 formal trials (2 × 8 × 20) and 32 (2 × 8 × 2) filler trials. Before the formal experiment began, participants completed 20 practice trials with feedback.

6. Results

Sigmoid functions were fitted to participants'enumeration Error Rates (ERR) under the single-task (denoted as no_load), dual-task low-load (low_load), and dual-task high-load (high_load) conditions. Subitizing capacity was then calculated for each participant across the three conditions, and statistical tests were performed on the 20 participants whose goodness-of-fit (R^2) was greater than 0.6 (see ***Supplementary material S4* for details).** The results (see Fig. 6) indicated a significant main effect of load level ($F(1.375,26.134) = 5.218$, $p = .021$, $\eta_p^2 = 0.215$). Post-hoc analysis showed that the subitizing capacity in the no_load condition (M = 4.219, SE = 0.367) was significantly higher than in the high_load condition (M = 3.108, SE = 0.189), $t(19) = 2.861$, $p = .030$, Cohen's d = 0.895. Similarly, the subitizing capacity in the low_load condition (M = 3.634, SE = 0.176) was also significantly higher than in the high_load condition ($t(19) = 2.658$, $p = .047$, Cohen's d = 0.645).

Dual-Task Error Rate: We conducted a 2 (Working Memory Load: low vs. high) × 6 (Enumeration Set Size: 1–6) repeated-measures ANOVA (see Fig. 7A). The results revealed a significant interaction between Working Memory Load and Enumeration Set Size ($F(5,115) = 3.425$, $p = .006$, $\eta_p^2 = 0.130$), indicating that the effect of high vs. low load on enumeration performance varied across different set sizes. Simple effects analysis showed that when the enumeration set size was 2 ($F(1,24) = 10.40$, $p = .004$, $\eta_p^2 = 0.286$), the participants' enumeration error rate was significantly higher in the high-load condition (M = 0.162,SE = 0.026) compared to the low-load condition (M = 0.119,SE = 0.026), $t(23) = 3.23$, $p = .0037$, Cohen's d = 0.0.658.

A similar significant difference in error rate was observed between the high-load (3, M = 0.433,SE = 0.040; 4: M = 0.563,SE = 0.037) and low-load (3, M = 0.331,SE = 0.044; 4: M = 0.506,SE = 0.039) conditions for set sizes 3 ($F(1,23) = 13.62$, $p = .001$, $\eta_p^2 = 0.382$) and 4 ($F(1,23) = 4.30$, $p = .050$, $\eta_p^2 = 0.167$), $t(23) = 3.69$, $p = .0012$, Cohen's d = 0.0.753 and $t(23) = 2.07$, $p = .0496$, Cohen's d = 0.0.423 respectively.

However, this difference between high and low load disappeared for the relatively large enumeration set sizes of 5 to 7 ($ps > 0.05$). This demonstrates that working memory load affects enumeration task performance, with higher error rates under high load. Crucially, this load modulation was confined to the small number range, indicating that working memory load only modulates subitizing performance and does not significantly impact estimation performance based on the ANS. This is consistent with our prediction and indicates that visual working memory and tactile subitizing share the object individuation resource. Furthermore, the repeated-measures ANOVA showed a significant main effect of Working Memory Load ($F(1,23) = 7.214$, $p = .013$, $\eta_p^2 = 0.239$); the enumeration error rate was lower in the low-load condition (M = 0.522,SE = 0.020) compared to the high-load condition (M = 0.550,SE =

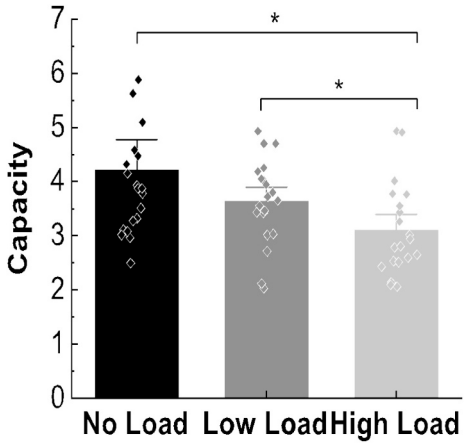

Fig. 6. Capacity of numerosity perception under different visual working memory loads. The bar charts represent group mean data, the diamonds represent individual subject data, and the error bars indicate the standard error. Asterisks represent significance, where *$p < .05$, **$p < .01$, and ***$p < .001$.

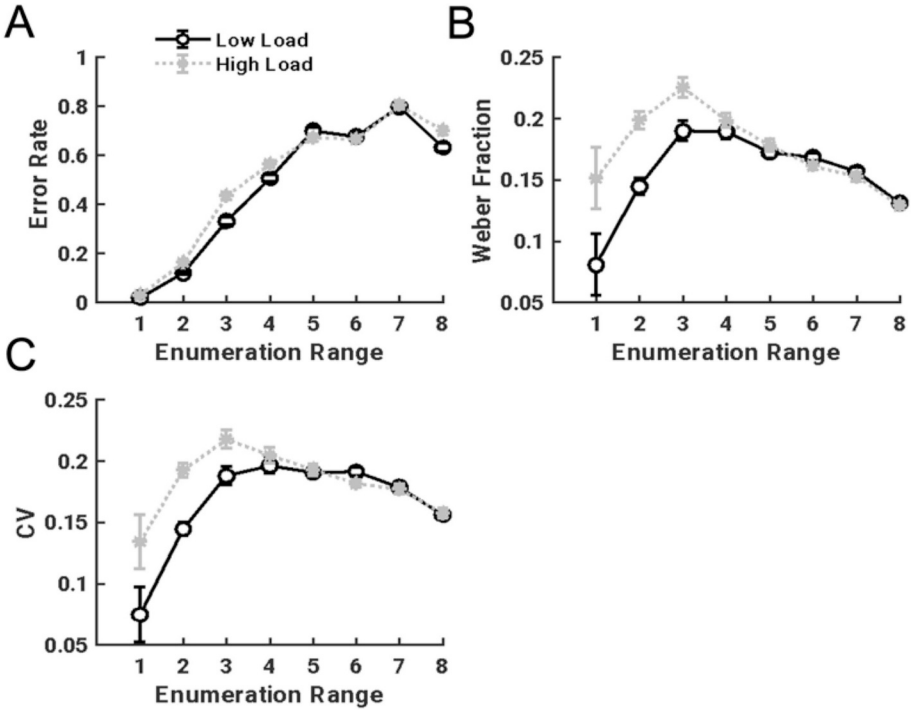

Fig. 7. Results of the numerosity enumeration task in the dual-task paradigm for Experiment 2. The black line represents the low-load condition, under which subjects were required to maintain memory for two visual colored block locations while completing the enumeration task. The grey line represents the high-load condition, under which subjects were required to maintain memory for four visual colored block locations while completing the enumeration task. Error bars indicate the standard error.

0.021), $t(23) = -2.686$, $p = .0132$, Cohen's d = 0.0.548. The main effect of Enumeration Set Size was also significant ($F(3.104,71.402) = 85.277$, $p < .001$, η_p^2=0.788); the error rate continuously increased with increasing set size. Post-hoc tests showed significant differences between all set sizes except 5 and 6 ($ps < 0.01$).

Additionally, to more directly illustrate the differential modulation of visual working memory load on tactile subitizing and estimation performance, we recategorized the data. Set sizes 2 to 4 were grouped as the small number range, and 5 to 7 as the large

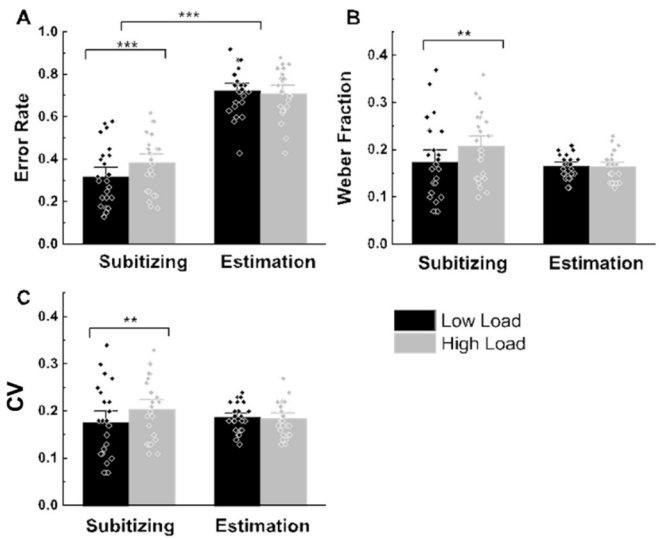

Fig. 8. Results of the numerosity enumeration task in the dual-task paradigm for Experiment 2. The bar charts represent group mean data, the diamonds represent individual subject data, and the error bars indicate the standard error. Asterisks represent significance, where *$p < .05$, **$p < .01$, and ***$p < .001$.

number range. A 2 (Working Memory Load) × 2 (Number Range: Small and Large) repeated-measures ANOVA was then performed (see Fig. 8A). The results showed a significant interaction between Working Memory Load and Number Range ($F(1,23) = 12.177$, $p = .002$, η_p^2=0.346). Further analysis re-validated the specificity of working memory load's modulation on subitizing performance: specifically, in the small number range ($F(1,23) = 19.73$, $p < .001$, η_p^2=0.455), the enumeration error rate was lower in the low working memory load condition (M = 0.319, SE = 0.029) compared to the high working memory load condition (M = 0.386, SE = 0.027), $t(23) = -4.44$, $p = .0002$, Cohen's d = .-0.907. No such difference was observed in the large number range, indicating no significant effect of working memory load on estimation performance. The main effect of Working Memory Load was significant ($F(1,23) = 7.214$, $p = .013$, η_p^2=0.239); the enumeration error rate was higher under high load (M = 0.550, SE = 0.021) compared to low working memory load (M = 0.522,SE = 0.020),

$t(23) = 2.686$, $p = .0132$, Cohen's d = 0.0.548. The main effect of Number Range was also significant ($F(1,23) = 149.454$, $p < .001$, η_p^2=0.867); the error rate was lower in the small number range (M = 0.352,SE = 0.027) compared to the large number range (M = 0.719, SE = 0.022), $t(23) = -12.225$, $p < .001$, Cohen's d = −2.495.

We implemented additional analysis for Experiment 2, and found the results were highly consistent with Experiment 1, re-confirming the range-specific nature of the cross-modal interference. Specifically, a significant interaction between WM Load and Number Range was observed for both Weber Fraction ($F(1,23) = 15.775$, $p = .001$, η_p^2=0.407) and Coefficient of Variation ($F(1,23) = 12.139$, $p = .002$, $\eta_p^2 = 0.345$), where high load exclusively reduced precision for small numbers (2–4). Baseline-corrected analyses (Delta Error) also revealed a significant interaction ($F(1,23) = 7.359$, $p = .012$, η_p^2=0.242), indicating that high tactile load more severely disrupted accuracy in the subitizing range ($F(1,23) = 11.15$, $p = .003$, $\eta_p^2 = 0.316$). Crucially, single-task controls showed no significant main effects or interactions involving load (ps > 0.05), excluding non-task-related processing as an explanation. These results strengthen the evidence that tactile working memory selectively competes for resources required for visual subitizing (see ***Supplementary materials S2*: additional analysis for Experiment 2**).

Combined Exploratory Analysis: Finally, we combined the baseline-subtracted data from Experiment 1 and Experiment 2 for an exploratory analysis. A 2 (Working Memory Load) × 2 (Number Range) × 2 (Task Type) repeated-measures ANOVA revealed a significant two-way interaction between Working Memory Load and Number Range for Delta Error. Simple effects analysis showed that when the number range was small ($F(1,47) = 33.640$, $p < .001$, $\eta_p^2 = 0.424$), the Delta Error value was significantly larger under high working memory load (M = 0.137, SE = 0.020) compared to the low working memory load condition (M = 0.062,SE = 0.021), Specifically, in Experiment 1, the high load condition produced significantly greater Delta Error than the low load condition ($t(24) = -5.32$, p < .001, Cohen's d = −1.06); similarly, in Experiment 2, the high load significantly increased Delta Error compared to the low load ($t(23) = -3.34$, $p = .003$, Cohen's d = −0.68). Conversely, in the large number range, no significant difference was found between high and low working memory loads in either Experiment 1 ($t(24) = -1.08$, $p = .291$, Cohen's d = −0.22) or Experiment 2 ($t(23) = 0.18$, $p = .856$, Cohen's d = 0.04). No significant difference was found between high and low working memory loads in the large number range. This is consistent with the results of Experiment 1 and Experiment 2, suggesting that the cross-modal working memory task load primarily modulates subitizing performance in terms of enumeration accuracy. The main effect of Working Memory Load for Delta Error was significant ($F(1,47) = 16.909$, $p < .001$, η_p^2=0.265), specifically, Delta Error was significantly lower under low working memory load (M = 0.110, SE = 0.017) compared to high working memory load (M = 0.152,SE = 0.018), $t(47) = 4.11$, $p < .001$, Cohen's d = 0.59.

Furthermore, the main effect of Number Range was significant for Delta Error ($F(1,47) = 6.399$, $p = .015$, η_p^2=0.120), Weber Ratio ($F(1,47) = 9.585$, $p = .003$, η_p^2=0.169), and CV Ratio ($F(1,47) = 27.993$, $p < .001$, η_p^2=0.373). Paired comparisons revealed that Delta Error was significantly larger in the large number range (M = 0.162, SE = 0.022) compared to the small number range (M = 0.100, SE = 0.020), $t(47) = 2.53$, $p = .015$, Cohen's d = 0.36. Similarly, Weber Ratio was significantly higher in the large range (M = 1.346, SE = 0.061) versus the small range (M = 1.045, SE = 0.093), $t(47) = 3.10$, $p = .003$, Cohen's d = 0.44. CV Ratio also showed a significant increase in the large range (M = 1.565, SE = 0.082) compared to the small range (M = 1.043, SE = 0.089), $t(47) = 5.29$, $p < .001$, Cohen's d = 0.76. However, no significant main effect of Task Type was observed across any of the three dependent variables (Delta Error: $F(1,47) = 3.49$, $p = .068$, η_p^2==0.069; Weber Ratio: $F(1,47) = 2.03$, $p = .161$, η_p^2==0.041; CV Ratio: $F(1,47) = 2.82$, $p = .100$, η_p^2==0.057), indicating a general modulation of subitizing performance by the cross-modal working memory task load.

6.1. Working memory performances across two experiments

6.1.1. The role of object individuation in subitizing

To systematically investigate whether tactile subitizing relies on object individuation —a capacity-limited attentional mechanism—we included the analyses for two experiments focusing on unimodal and cross-modal resource competition **(also see supplementary material S3 for details).**

In Experiment 1 ($N = 31$), we employed a correlational design to examine the relationship between tactile subitizing capacity (S), tactile working memory (WM) capacity (K), and Approximate Number System (ANS) precision (w). Pearson correlations revealed a robust positive relationship between subitizing and WM capacities ($R = 0.612$, $p < .001$). Crucially, neither metric correlated with estimation precision (S vs. w: $R = 0.057$, $p = .761$; K vs. w: $R = -0.04$, $p = .829$), providing initial evidence that tactile subitizing shares object individuation resources with WM rather than relying on the ANS.

Experiment 2 ($N = 21$) further established this causal link using a dual-task paradigm. Sigmoid fitting showed that high tactile WM

load significantly reduced subitizing capacity compared to both no-load and low-load baselines ($F(1.486, 29.728) = 15.545$, $p < .001$, $\eta_p^2 = 0.437$). A 2 (Load)x 2 (Range) repeated-measures ANOVA revealed significant interactions for both error rates ($F(1,23) = 24.025$, $p < .001$, $\eta_p^2 = 0.511$) and precision (WF: $F(1, 23) = 16.603$, $p < .001$, $\eta_p^2 = 0.419$), with high load selectively impairing performance in the small number range (2–4) while leaving the large number range (5–7) unaffected. Baseline-corrected analyses (Delta ERR, Delta WF, Delta CoV) also confirmed these findings, ruling out physical stimulus differences and isolating the effect to resource competition within the object individuation system.

The cost of this competition was also evident in working memory performance. In unimodal tactile tasks, a significant load x numerosity interaction was found ($F(7, 161) = 2.68$, $p = .012$), with high load significantly increasing error rates across nearly all numerosity levels ($p < .001$). In cross-modal (tactile-visual) contexts, a mixed-design ANOVA revealed a significant Task x Load interaction ($F(1, 767) = 17.12$, $p < .001$). Dual-task error rates significantly exceeded single-task baselines in 68.75% of tested conditions, and the magnitude of the WM load effect was significantly larger in the dual-task group ($p = .031$).

Collectively, these results demonstrate that subitizing—whether unimodal or cross-modal—is a resource-dependent process that competes with working memory for a shared pool of Object Individuation resources, distinct from the mechanisms governing large-number estimation.

7. Discussion

The results of Experiment 2 demonstrate that visual working memory load modulates tactile subitizing performance. Specifically, participants exhibited a higher error rate and lower precision in subitizing under high working memory load compared to low working memory load. Furthermore, the results indicated a significant reduction in subitizing capacity under the high working memory load condition relative to the low working memory load condition. Crucially, this modulatory effect was absent during the estimation process.

These findings are consistent with the results from Experiment 1, suggesting that the object individuation processes between the visual and tactile modalities are mutually modulatory. We attribute this to the fact that the object individuation resource is shared across modalities and tasks. Consequently, the concurrent performance of cross-modal subitizing and working memory tasks leads to competition for the limited object individuation resource. The high working memory load, which consumes a greater proportion of the object individuation resource, thus imposes a more severe impact on subitizing performance. Since estimation relies on the ANS, the degree of object individuation resource consumption by the working memory task does not exert a significant modulatory effect on it.

Moreover, the single-task analysis showed that when only the physical stimuli of the working memory task were presented without requiring cognitive processing, different working memory loads did not modulate subitizing performance, and there was no significant overall effect of the working memory task's physical stimuli on the enumeration task. This rules out the alternative explanation that the modulation of subitizing performance by different memory loads was caused by physical stimulus differences between the high and low load conditions. Finally, by using the single-task results as a baseline to calculate difference scores (Delta Error) and ratio scores (Weber Ratio and CV Ratio) and consistent with Experiment 1, the modulatory effect of working memory load on subitizing performance persisted in the Delta Error analysis. However, this load-dependent difference disappeared in the precision indicators.

These results indicate that visual working memory and tactile subitizing share the OI resource, and the modulation of subitizing performance by the cross-modal working memory task load primarily manifests as a change in accuracy. In conclusion, the results of Experiment 2 demonstrate that visual working memory modulates tactile subitizing performance.

8. General discussion

Distinguishing objects from the background is prerequisite for interacting with the external environment, a goal achieved by the object individuation process through the utilization of location information (Chakravarthi & Herbert, 2019; Goodhew, 2019; Poncet & Chakravarthi, 2021; Xu & Chun, 2009). The central question addressed in this research is whether object individuation processes across different modalities share a common OI resource.

With respect to cross-modal enumeration, one of the central debates in cognitive neuroscience concerns whether the enumeration of tactile and visual events relies on a shared, modality-independent mechanism or if it is constrained by sensory-specific object individuation processes. This discussion is heavily informed by the “metamodal” hypothesis (Park and Fine, 2024), which suggests that certain brain regions are organized by the specific computations they perform rather than the sensory input they receive. Seminal research by Sadato et al. (1996, Sadato et al., 1998) provided early evidence for this by demonstrating that the primary visual cortex (V1)—traditionally viewed as a purely visual processor—is robustly activated during tactile Braille reading in blind individuals. This recruitment of “visual” areas for complex tactile discrimination implies that the neural architecture for spatial analysis and individuation may be inherently metamodal. Furthermore, Sadato et al. (2002) identified a critical period for this cross-modal plasticity, suggesting that while the brain possesses a flexible, common system for representing objects and numerosity, the integration of these tactile and visual streams is deeply influenced by early developmental experience. Together, these studies support the view that enumeration may be governed by a unified system that individuates “items” regardless of whether they are perceived through sight or touch.

Enumeration entails the attentional selection (“object individuation”) before the identity of object recognition has been achieved, which could be constrained by the limited working memory capacity (WMC). The relationship between WMC and attentional selection represents a fundamental cornerstone of cognitive architecture. Contemporary perspectives suggest that WMC is not merely a passive

storage buffer but a dynamic system that "turns attention inside out" to serve goal-directed behavior (van Ede & Nobre, 2023). Central to this interaction is the "focus of attention" (FoA), which serves as a common resource limit for both the maintenance of mental representations and the execution of simultaneous processing tasks, including the embedded process linking attention and WMC under cognitive overload (Atkinson & Shiffrin, 1968; Cowan et al., 2024; Park and Fine, 2024).

Empirical evidence emphasizes that attentional selection is a prerequisite for identity access. According to stimulus-driven accounts, an object's identity only becomes available for cognitive manipulation after it has been prioritized by the attentional spotlight (Theeuwes, 1991, 1992, 2025). This bottleneck is particularly evident in tasks requiring simultaneous enumeration and maintenance, where the competition for limited-capacity "slots" or neural resources necessitates efficient computation (Bays et al., 2024). While high-priority items can be selectively buffered within WMC, this prioritization often comes at the cost of increased vulnerability to external interference (Allen & Ueno, 2018) and a constant struggle between perceptual recency and executive control (Hitch et al., 2018).

Furthermore, the "Time-Sharing" model suggests that WMC and attentional processing operate through rapid temporal switching (Barrouillet et al., 2023). For instance, in the context of visual search, although top-down templates in WMC guide the search process (Wolfe, 2021), certain inhibitory mechanisms—such as learning to suppress frequent distractors—may operate independently of the current working memory load (Gao & Theeuwes, 2020). Taken together, these findings suggest that while WMC and attention are functionally distinct, they are deeply interleaved systems that co-limit the human capacity to enumerate, select, and maintain information in the face of environmental complexity, such as in concurrent enumeration and working memory tasks.

Here we used two cross-modal dual-tasks to investigate this question. In Experiment 1, participants completed a dual-task composed of tactile working memory and visual enumeration, revealing that the load of tactile working memory modulated visual subitizing performance. Specifically, participants showed a higher error rate and lower precision in subitizing under high tactile working memory load compared to low load. The results also indicated a significant reduction in subitizing capacity under high working memory load. Similar results were found in Experiment 2, which employed a dual-task composed of visual working memory and tactile enumeration. These findings align with results observed in the visual single-modality (Piazza et al., 2011), suggesting that subitizing and working memory tasks in the visual and tactile modalities share the object individuation resource—meaning the object individuation process operates on location information, regardless of its modality or format.

To exclude confounds related to physical stimulus differences, we conducted single enumeration tasks using the same physical stimuli. The analysis showed that when only the physical stimuli of the working memory task were presented without requiring cognitive processing, different working memory loads did not modulate subitizing performance, and there was no significant overall effect of the physical stimuli across different loads on the enumeration task. This rules out the alternative explanation that the load-dependent modulation of subitizing performance was caused by differences in the physical stimuli of the working memory task between the high and low load conditions.

Moreover, the modulation of subitizing by the cross-modal working memory task was more pronounced in accuracy than in precision. Consistent with Experiment 1, when using the single-task results as a baseline to calculate difference scores (Delta Error) and ratio scores (Weber Ratio and CV Ratio), the modulatory effect of working memory load on subitizing performance persisted in the Delta Error analysis, but this load-dependent difference disappeared in the precision indicators, showing indicators of differential sensitivities.

One of the central debates in working memory (WM) research addresses whether its resources are shared across modalities (e.g., visual, verbal) or if multiple, specialized storage units coexist (Katus & Eimer, 2018). While the common dual-task paradigm frequently demonstrates cross-task interference (Cowan et al., 2014; Fougnie et al., 2018; Salmela et al., 2014), some, like Cocchini et al. (2002), argued that this interference reflects general dual-task coordination costs, pointing out that it also occurs between WM and non-WM tasks such as Multiple Object Tracking (MOT)(Cocchini et al., 2002). Crucially, however, MOT and WM are now widely believed to share the Object Indexing process (Feldman & Tremoulet, 2006; Mitroff & Alvarez, 2007; Pylyshyn, 2004). This suggests that the observed interference may instead reflect the specific sharing of the object individuation resource. This interpretation is supported by experimental results indicating that WM load did not modulate performance based on the Approximate Number System (ANS) process in dual-tasks, confirming that the observed cross-modal modulatory effect is due to the cross-modal sharing of the object individuation resource.

Beyond WM, capacity-limited mechanisms like subitizing and MOT are vital for interacting with the environment (Xu & Chun, 2009). The initial focus on the visual modality (Cowan, 2001; Kaufman & Lord, 1949; Pylyshyn & Storm, 1988; Wurm et al., 2019; Xu, 2021) is shifting toward a cross-modal perspective (Anobile et al., 2016; Anobile et al., 2018; Attout et al., 2017; Katzin et al., 2019; Morimoto, 2020; Nieder, 2012, 2017; Wu et al., 2018). Behavioral and electrophysiological evidence suggests subitizing is an abstract, generalized cognitive process independent of sensory modality (Nieder, 2012, 2020; Nieder et al., 2006; Tian & Chen, 2018; Viswanathan & Nieder, 2020), which is consistent with numerosity-specific representations found in the right Lateral Prefrontal Cortex (LPFC) (Uluc et al., 2020), a single neural mechanism covering subitizing and estimation (Cai et al., 2021), and early visual processing linked to Fourier power (Paul et al., 2022). This abstract nature is further highlighted by modal-independent deficits in developmental dyscalculia (DD) (Cohen et al., 2019) and atypicalities in Autism Spectrum Disorders (ASD)(Meaux et al., 2014), leading to the re-conceptualization of subitizing as an enumeration subprocess (Katzin et al., 2019).

To summarize the present findings, we proposed *A Hierarchical Cross-Modal Architecture of Numerosity and Memory* (Fig. 9). The cognitive processing of sensory stimuli is governed by a hierarchical dual-pathway architecture that differentiates between Object Individuation and Object Identification (Xu & Chun, 2009). Both visual and tactile modalities feed into these pathways, but they are processed according to distinct informational priorities. The Object Individuation pathway is primarily driven by position information, operating as a low-resolution mechanism with a fixed capacity of approximately four objects (Cowan, 2001). Crucially, this process

remains independent of sensory modality, object complexity, and encoding demands, serving as the shared foundational mechanism for both subitizing and spatial working memory (Pylyshyn, 1989).

In contrast, the Object Identification pathway prioritizes feature information to achieve high-resolution representations. This stage is characterized by a variable capacity (typically $\leq$4 objects) and is highly sensitive to object complexity and specific task demands, primarily supporting non-spatial working memory (Piazza et al., 2004). While individuation typically precedes identification, the two stages can interact, with recognition outcomes reciprocally refining the individuation process. Ultimately, while resources for individuation can be distributed across modalities, the total capacity remains strictly limited, a constraint that directly impacts the efficiency of subitizing and spatial memory performance across the visual and tactile domains.

Although object individuation (Kahneman et al., 1992; Xu & Chun, 2009), attentional indexing (Pylyshyn, 1989), and spatial working memory (Luck & Vogel, 1997) are distinct constructs, all three are location-based, capacity-limited to roughly four items (Cowan, 2001), and supported by overlapping frontoparietal regions. Attentional indexing in particular has been proposed as the mechanism underlying subitizing itself (Trick & Pylyshyn, 1994). Each account therefore predicts the interference pattern observed here. Our paradigm establishes that working memory and subitizing share such a resource, and the restriction of interference to the subitizing range favors an individuation-based account; however, it does not isolate which of these closely related processes constitutes that resource. Future work dissociating individuation demands from location maintenance (e.g., comparing location- versus feature-based WM loads) will be needed to adjudicate between them.

A second, equally important contribution of the present study is the clean dissociation between subitizing and estimation. Although the existence of two enumeration regimes is well established in the visual domain, recent computational work has challenged it, proposing that a single approximate mechanism with Weber-like scaling can account for number psychophysics across the entire range (Cheyette et al., 2024; Cheyette & Piantadosi, 2020; Park & Huber, 2022). Our results speak directly to this debate: if subitizing and estimation were two manifestations of one unitary mechanism, an orthogonal working memory load should have degraded performance across all numerosities. Instead, interference was confined to the subitizing range, providing process-level evidence for two functionally dissociable mechanisms — consistent with psychophysical and neuropsychological evidence for a dedicated small-number system (Anobile et al., 2020; Anobile et al., 2021) — and echoing earlier demonstrations that attentional resources are required for subitizing but not estimation (Burr et al., 2010). Critically, we extend this dissociation beyond vision: the same selective vulnerability emerged whether the enumeration task was visual or tactile, and whether the interfering load was tactile or visual, suggesting that the subitizing/estimation boundary reflects an amodal architectural property of enumeration rather than a feature of any single sensory system. This cross-modal selectivity also constrains computational models: systems that reproduce the subitizing pattern as an emergent property of capacity-limited processing (Testolin et al., 2020) will need to operate on modality-independent object representations to capture our data. We therefore regard the dissociation not merely as a manipulation check but as a core result, one that ties the small-number range to a shared, location-based individuation resource while leaving estimation to a separate, resource-insensitive approximate mechanism.

Recent neuroimaging studies of cross-modal subitizing and WM tasks consistently identify frontoparietal regions as playing a crucial role in these shared cognitive mechanisms. Specifically, electrophysiological research in monkeys has pinpointed neuronal clusters in the Intraparietal Sulcus (IPS) and LPFC that respond to object numerosity, independent of sensory modality (visual or auditory) or presentation format (simultaneous or sequential) (Nieder, 2012, 2020; Nieder et al., 2006; Viswanathan & Nieder, 2020). Furthermore, fMRI studies have successfully localized brain regions concurrently responsible for visual and tactile working memory, including the Inferior Parietal Lobule (IPL), Superior Parietal Lobule (SPL), and Prefrontal Cortex (PFC) (Wu et al., 2018). Collectively, these findings strongly suggest that the frontoparietal cortex is the core brain region responsible for realizing the modality-shared object individuation process. Future research should leverage neuroimaging techniques to thoroughly investigate the cognitive neural mechanisms by which the OI resource is shared across diverse modalities and task formats.

Studies in human

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place.

This study was approved by the Academic Affairs Committee of the School of Psychological and Cognitive Sciences at Peking University. (Approval No. #2021-10-18)

CRediT authorship contribution statement

Chunmiao Lou: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lihan Chen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Informed consent and patient details

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

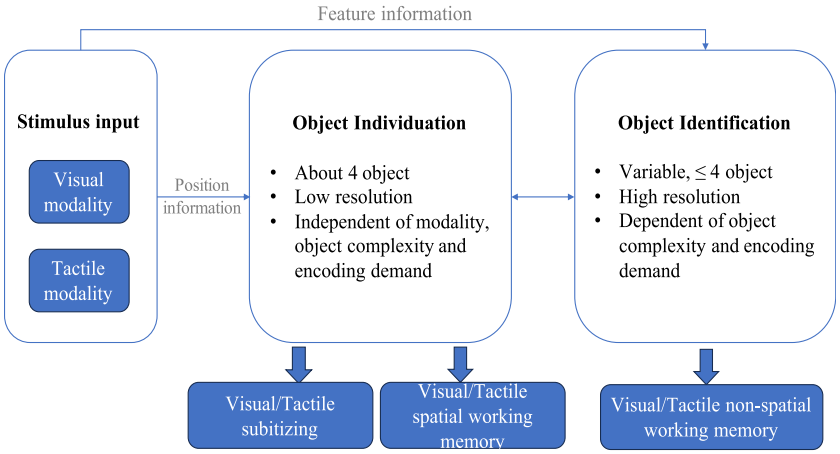

Fig. 9. The Hierarchical Cross-Modal Architecture of Numerosity and Memory: A Dual-Pathway Model of Position-Based Individuation and Feature-Based Identification. The cognitive processing of stimuli follows two distinct pathways depending on the type of information being prioritized: Object Individuation and Object Identification. Both visual and tactile modalities serve as stimulus inputs that feed into these pathways. The Object Individuation pathway is primarily driven by position information and is characterized by a capacity of approximately four objects with low-resolution representation. Crucially, this process is independent of sensory modality, object complexity, and encoding demands. It serves as the foundational mechanism for both subitizing (visual or tactile) and spatial working memory. In contrast, the Object Identification pathway processes feature information to achieve high-resolution representations. Unlike individuation, this pathway has a variable capacity (typically ≤4 objects) and is highly dependent on the complexity of the objects and specific encoding demands. This more intensive processing stage supports non-spatial working memory tasks. While individuation typically precedes recognition, the two stages can interact, with recognition outcomes reciprocally refining the individuation process. Ultimately, while resources for Object Individuation can be distributed across modalities, the total capacity remains fixed at approximately four objects, a constraint that directly impacts the efficiency of subitizing and spatial memory tasks.

Declaration of competing interest

We declare no conflict of interest in this research. Financial Support: STI2030-Major Project 2021ZD0202600, and Natural Science Foundation of China (T2192932) to L.C.

Appendix A. Supplementary data and analysis

Supplementary data and analysis to this article can be found online at https://doi.org/10.1016/j.cogpsych.2026.101830.

Data availability

Data will be made available on request.

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