



Asymmetric switch cost between subitizing and estimation in tactile modality

Chunmiao Lou¹ · Huanke Zeng¹ · Lihan Chen¹

Accepted: 31 January 2022

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract

Subitizing (enumerating four or fewer objects) and estimation (enumerating five or more objects) are two rapid enumeration processes. The relationship between them remains undetermined, especially in tactile modality. The present study used a double enumeration paradigm to assess switch costs. In this paradigm, participants were required to enumerate two sequentially presented arrays of tactile stimuli, each with a set size either within or outside of a predetermined subitizing range. When enumeration process switched between subitizing and estimation, participants' response to the second array showed a higher error rate and worse precision, relative to no processing switch conditions. Meanwhile, the switch costs exhibited an asymmetry pattern - the switch from estimation to subitizing gave rise to a worse precision than the switch from subitizing to estimation did. During a switch from subitizing to estimation, the switch costs nearly vanished, since subitizing had already mobilized both approximate number representation system (ANS) and object individuation (OI). The switch costs also disappeared when inter-stimulus intervals (ISIs) between the two arrays were extended (i.e., preparation effect). Our results supported "dual component hypothesis" that subitizing activated OI and ANS processes while estimation only activated ANS, corresponding with evidence from visual modality. Taken together, the present findings suggest that tactile subitizing mobilizes both OI and ANS processes, and non-symbol number representation is modality-independent.

Keywords Tactile enumeration · Subitizing · Estimation · Switch cost · Asymmetry

Introduction

Non-symbolic number presentation, such as estimating the number of elements in a given set, is of great significance to human survival and civilization (Nieder, 2012). This remarkable ability has developed ever since the very beginning of

one's life (Nieder, 2016). Some studies showed that 6-month-old infants were able to distinguish visual arrays with a large number of elements (e.g. 8 vs. 16) based on numerosity (de Hevia & Spelke, 2010; Xu et al., 2005; Xu & Spelke, 2000), reflecting a pressing need for number sense to accommodate the environments. The "number sense theory" (Arrighi et al., 2014; Burr & Ross, 2008; Cicchini et al., 2016) believes that numerosity is represented abstractly in mind, regardless of specific modalities and the spatio-temporal layout of individual elements (Nieder, 2012, 2016; Nieder & Dehaene, 2009). For instance, an abstract number of "three" could be conveyed through three Braille points (tactile modality), three bird songs in a sequence (auditory modality), or three pictures (visual modality).

The abstract and supramodal nature of non-symbolic number representation has been supported by recent studies using brain imaging and intracranial electrodes recordings (Eger et al., 2003; Hofstetter et al., 2021; Nieder, 2012, 2016, 2017; Piazza et al., 2006). For example, Nieder (2012) trained monkeys to evaluate and match the numbers of visual and auditory modalities in the same trial, and recorded

Significance Statement

Subitizing and estimation are two critical enumeration processes for non-symbol numbers enumeration. While the evidence from the visual and auditory modalities was sufficient, there were relatively fewer investigations on the switch costs between the them in tactile modality. Here we implemented non-symbol tactile enumeration tasks and revealed object individuation (OI) processes during the asymmetric transition for switch cost, and proved non-symbol numbers representation was on abstract level and modality-independent.

✉ Lihan Chen
CLH@pku.edu.cn

¹ School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing 100871, China

neuronal responses in the ventral intraparietal area (VIP) and the lateral prefrontal cortex (LPFC) with intracranial electrodes. The results showed that neurons in both areas encoded numbers, no matter whether numbers were presented as auditory pulses, visual items, or both. This finding demonstrated the supramodal nature of non-symbolic number representation which was also largely independent of specific spatio-temporal presentation formats.

In visual domain, many studies used enumeration task which asked participants to count the number of items in a given set to investigate non-symbolic number presentation. Two classical perceptual processes have been identified in enumeration : subitizing (Kaufman et al., 1949) and estimation (Whalen et al., 1999). Subitizing refers to a rapid and accurate enumerating of small set numerosity that are up to about four. Estimation, in contrast, refers to a rapid but error-prone enumeration of larger numbers above four. The relationship between subitizing and estimation as well as the underlying characteristic mechanisms have received wide attention, but the conclusion has remained elusive (Attout et al., 2017; Katzin et al., 2019; Knops et al., 2014; Pomè et al., 2019; Revkin et al., 2008; Sengupta et al., 2017; Tian & Chen, 2018). Among the debates, three promising hypotheses were proposed. Here, we summarize them as “single estimation component hypothesis” (Dehaene & Changeux, 1993; Gallistel & Gelman, 1991), “single object-individuation component hypothesis” (Feigenson et al., 2004; Trick & Pylyshyn, 1994.; Xu, 2009) and “dual component hypothesis”(Anobile et al., 2012; Burr et al., 2010).

According to “single estimation component hypothesis”, subitizing is indeed a form of estimation in the small numerosity range (Dehaene & Changeux, 1993; Gallistel & Gelman, 1991). Compared with estimation, subitizing process exhibits higher precision. However, both subitizing and estimation are based on approximate number representation system (ANS) which assesses the number of items in an overall approximate fashion. Moreover, they obey Weber's law and their variances both grow in proportion to given set sizes. The reason for greater precision of subitizing is that the same numerical difference between two consecu-

object-individuation component hypothesis” and “dual component hypothesis” diverge on the role of estimation. The former suggests that estimation only operates on large numerosity range, while the latter emphasizes estimation operates over the entire range of numbers.

The above three hypotheses have been examined in the visual domain. Indeed, some tactile studies suggested there was also a rapid and accurate enumeration of small sets as in visual modality (Gallace et al., 2006, 2008; Riggs et al., 2006). Recently increased attention has been paid to the number representation in the tactile modality (Cohen, Aisenberg, & Henik, 2018a; Cohen, Arend, et al., 2018b; Cohen & Henik, 2016; Hochman et al., 2020; Tian & Chen, 2018). However, to the best of our knowledge, no research has examined the relationship between tactile subitizing and estimation so far. It is open to exploration whether these hypotheses in visual enumeration could apply to the tactile modality as well. The homologous neural bases underlying tactile and visual modalities, such as the lateral occipital complex (LOC) for object representations (Amedi, 2002; Amedi et al., 2001; Sathian & Zangaladze, 2002), motivated us to think that the two modalities could share the same mechanism for the number sense. Importantly, investigating the two enumeration processes (subitizing vs. estimation) in the tactile domain helps to further advance our understanding of the non-symbolic number representation.

In the present study, we developed a double enumeration paradigm to explore the relationship between underlying mechanisms of subitizing and estimation in tactile modality. Participants were required to enumerate two sequentially presented arrays of tactile pins on the right index finger. The double enumeration paradigm included the no switch condition (the numerical ranges of two tasks were the same) and switch condition (the numerical ranges of two tasks were different).

According to the previous studies, they used a paradigm where participants were first familiarized with two (or more) simple cognitive tasks and then asked to switch between these tasks on demand. The results showed that the task switch would generate a switch cost effect, identified by an increase in response time and a decrease in response accuracy on second task (Meiran, 1996; Monsell, 2003; Rogers & Monsell, 1995). There are several explanations for the nature of switch cost (if presented). One of the influential explanations is task-set reconfiguration (Logan & Gordon, 2001; Mayr & Kliegl, 2000; Monsell & Mizon, 2006). A “task set” is an organization of mental resources that will accomplish a particular cognitive task by inputting appropriate, mainly endogenous cognitive resources (Monsell, 2003). The task-set reconfiguration hypothesis assumes that during task switching (changing

the existing task to a different task), a reconstruction process of mental resources organization will take place. This process depletes the additional attentional resources, giving rise to the switch cost effect. Yet the attentional resources consumed by the reconstruction process in a switch task could recover over time. Therefore, switch cost effect will decrease as the interval between two tasks extends, which is referred as preparation effect (Arrington & Logan, 2004).

Importantly, we aimed to probe the relationship between the underlying mechanisms of two enumeration processes: subitizing and estimation. If tactile subitizing and estimation shared the same perceptual mechanism, there would be no switch cost caused by task switch itself, no matter the task order - subitizing shifted to estimation or estimation shifted to the subitizing. Alternatively, a robust switch cost effect would indicate a disassociation between mechanisms underlying subitizing and estimating. Meanwhile, according to the preparation effect, when the interval between two enumeration tasks increased, the additional resources consumed by the reconstruction process would recover, and the switch cost effect would weaken or even disappear in the switch condition.

In the present study, we designed and implemented three experiments to reveal the relationship between tactile subitizing and estimating. In Experiment 1, we determined a demarcation point between tactile subitizing range and estimation range. In Experiment 2, we used a double enumeration paradigm with two sequential arrays of tactile stimuli (S1 and S2) to explore the relationship between two enumeration processes (subitizing vs. estimation). Meanwhile, by manipulating the inter-stimulus intervals (ISIs) between two enumerations, we examined the possible preparation effect. In the present setting, changes in numerosity were always accompanied by changes in non-numerical properties of stimuli (DeWind et al., 2015; Piazza et al., 2018). Given that the item size (pins size) and the inter-distance between tactile pins were fixed in our experiment, the larger of the numerosity, the larger of the total surface to enclose the tactile stimuli. Therefore, the results of the switch condition could be contaminated by the change in non-numerical properties of stimuli, rather than the switches between subitizing and estimation. Thus, Experiment 3 served as a control test to exclude this above alternative explanation of Experiment 2. In Experiment 3, participants were required only to report the numerosity of either S1 or S2, so there was only the change in non-numerical properties of stimuli but no switch between subitizing and estimation.

E e i e 1

Method

Participants We determined the adequacy of our sample size according to the following two rationales. First, we performed a priori sample size estimation by GPower 3.1 (Faul et al., 2007). We took the effect size of the effect of numerosity ($\eta^2_p = .91$) observed in Riggs et al. (2006) and assumed an alpha of 0.05 and a power of 0.8 (ANOVA, repeated measures, within factors, and eight measurements). The result suggested a minimum sample size (N) was 2. Second, according to “rule-of-thumb” in a recent analysis of power in cognition experiments (Brysbaert & Stevens, 2018), an adequately powered experiment requires a total of 1,600 observations (Participants \times Trials) per cell of the relevant analysis. There were 192 trials in Experiment 1, in this case N should be larger than 8 ($1600/192 = 8.333$). Our $N = 21$ (4 males; mean age 19.61 ± 0.58) was two to three times larger and hence more than adequate for detecting effects similar to the study of Riggs et al. (2006). We recruited students with normal or corrected-to-normal vision from Peking University. All experiments were performed in compliance with the institutional guidelines set by the Academic Affairs Committee, School of psychological and Cognitive Sciences, Peking University, China. All participants provided written informed consent according to institutional guidelines, and were reimbursed for their time.

Apparatus We used the Piezo stimulator (QuaeroSys, Germany), which was composed of 20 tactile pins and with a maximum refreshing rate of 1 kHz, to deliver tactile stimuli. These tactile pins had a minimum distance of 2.5 mm between each other. Their intensity and duration were individually controlled by programming with Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997), implemented on MATLAB (MathWorks Inc.). We set intensity to the maximum for all tactile pins in all experiments. Fixation and instructions were displayed on a 15-inch Dell LCD monitor (1336×768 pixels, 60 Hz frame rate).

Procedure Each trial began with a fixation at the center of the screen for 500–1000 ms, then an alarming sound (70 Hz, 30 ms) was delivered, followed by the tactile pins (with number of 1–8 and duration of 1250 ms). The interval between the cueing sound and tactile stimuli was 50 ms. Participants reported tactile pin numbers by pressing a corresponding number on the numeric keypad. Before the formal test, there were 20 practice trials. And each numerical condition (1–8) was repeated 24 times, making up a total of 212 trials.

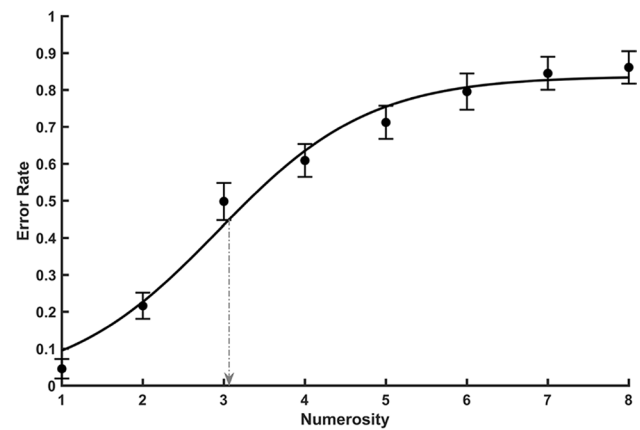


Fig. 1 The error rate result of Experiment 1. The curve showed the fitted sigmoid functions for average data. Arrows indicate tactile subitizing capacities measured from the inflection point of the fitting functions.

Results and Discussion

We compared the error rate (ERR) of participants' responses with a repeated-measured analysis of variances (ANOVA¹) and found a significant main effect of numerical range ($F(3.034, 60.861) = 134.12, p < .001, \eta^2_p = .87$). Post hoc analysis showed that, except for dyad comparisons among conditions with 6, 7, and 8 tactile pins, there was a significant difference in each comparison between two of the rest numerical conditions ($ps < .001$).

Recent research about visual enumeration suggested sigmoid function fitting as an efficient way to determine the subitizing range (Anobile et al., 2019; Piazza et al., 2011). Here we also applied sigmoid function fitting and according to the inflection point of sigmoid function defined the tactile subitizing range. The inflection point was defined as the point in which the second derivate of the sigmoid function equaled zero. The fitting results (see Fig. 1, the curve showed the fitted sigmoid function for average data and arrows indicate tactile subitizing capacities measured from the inflection point of the fitting functions) indicated a subitizing capacity of 3.05 ($SE_{(capacity)} = .20$; average $R^2 = .93, SE_{(R^2)} = .01$). To sum up, there was a subitizing effect when target numbers were small. In this case, the subitizing range was operationally defined as 1–3 for the following two experiments.

¹ In each ANOVA of each experiment, the Bonferroni correction for multiple comparisons was used in post-hoc tests. Whenever the Sphericity assumption was violated, we applied the Greenhouse-Geisser correction in each ANOVA

E e i e 2

Method

Participants Twenty-six healthy adult participants (9 males; mean age 22.01 ± 0.32) took part in the test. In Experiment 2, we focused on the numerical range of S1×numerical range of S2 interaction (switch cost effect) and the numerical range of S1×numerical range of S2×ISIs interaction (preparation effect). Thus, we took the effect size of the switch cost effect ($\eta^2_p = .497$) and the preparation effect ($\eta^2_p = .101$) observed in Graham and Lavric (2021) and assumed an alpha of 0.05 and a power of 0.8. (ANOVA, repeated measures, within factors, two measurements and four measurements). The result showed that our sample size was larger than the required sample sizes ($N = 4$ and $N = 14$) to obtain effect sizes of switch cost effect and preparation effect respectively. At the same time, we also examined our sample size in the light of recent recommendations of Brysbaert and Stevens (2018). In our design the total number of observations per cell (for the above interactions) was 33280 (26 participants×1280 trials), which was more than adequate. Informed consent was collected before experiments.

Apparatus and Procedure We used a double enumeration paradigm whose tactile stimuli were consistent with Experiment 1. According to the result of Experiment 1, we categorized tactile stimuli as within the subitizing range (1-3) and within the estimation range (6-8). Meanwhile we treated tactile stimuli containing 4 or 5 tactile pins as fillers, which made up 25% of total trials. Here, under the no-switch condition the numerical ranges of the first and second array remained consistent, that is, subitizing-subitizing and estimation-estimation conditions (hereafter “S-S” and “E-E”). Correspondingly, the switch condition referred to the trials in which the numerical ranges differed between two arrays, that is, estimation-subitizing and subitizing-estimation conditions (hereafter, “E-S” and “S-E”).

In each trial, participants were required to enumerate two sequentially presented arrays of tactile pins (S1 and S2 respectively) with the set size of each array either within or out of a predetermined subitizing range (1-3 tactile pins), each preceded by an alarming sound (70 Hz, 30 ms) as in Experiment 1. The alarming sound served as a cue that tactile stimuli were about to appear, and also helped the participants distinguish the first array of stimuli from the second one. To investigate the possible preparation effect, we implemented four levels of ISIs between two tactile stimuli: 100 ms, 250 ms, 400 ms, or 550 ms. The ISIs between two tactile stimuli comprised three segments: the blank followed the first tactile pins array (different in Experiment 2a-2d: 2a: 20

ms; 2b: 170 ms; 2c: 320 ms; 2d: 470 ms), the alarming sound (70 Hz, 30 ms) and the fixation before the second array (50 ms). The experiment was divided into four -tests based on various ISIs (2a: 100 ms; 2b: 250 ms; 2c: 400 ms; 2d: 550 ms). To minimize the potential influence of working memory on different sub-experiments, before participants issued responses, there was a blank interval with one of the four durations: 500 ms (2a), 350 ms (2b), 200 ms (2c), or 50 ms (2d). This could ensure that the total duration of each trial in the four sub-experiments was consistent (3680 ms - 4180 ms, including the fixation duration: 500 -1000 ms). There were 320 trials in each sub-experiment, 80 of which were fillers. There were 2 (the numerical range of S1: subitizing and estimation) ×2 (the numerical range of S2: subitizing and estimation) conditions and each condition was repeated 60 times in each sub-experiment. Given that the response of S2 was more susceptible to the switch cost effect, we discarded responses of S1 and focused on the response of S2 in the following results analysis. Therefore, in each condition, we further balanced the target number (1, 2, 3 or 6, 7, 8) of the second enumeration task and each number was repeated 20 times. In a typical trial, two arrays of tactile pins were presented sequentially and the durations were both 1250 ms. Participants were asked to give their responses for enumeration task 1 and 2 sequentially by pressing appropriate number keys at the end of each trial. There was no time limit for responses (see Fig. 2). Participants completed a baseline task that was exactly the same as Experiment 1 and then four tests in Experiment 2 (2a-2d) on two separate days. The test orders were randomized across participants. And all participants were paid for their participation.

Results and Discussion

Given that the switch cost could only impact reporting S2, we discarded responses of S1 and focused on the responses of S2. We first analyzed the ERR of S2 as in Experiment 1. However, it is important to distinguish the two forms of error, accuracy and precision. The accuracy informs us the direction of the error, and the precision tells us how reliably participants can make enumeration judgments. Another problem with error rate is that its dualism might fail to index the magnitude of errors: for example, confusing 2 with 3 is scored equally to confusing 2 with 5. We hence also analyzed the precision of the responses of S2, which was operationally defined as coefficient of variation (CoV: std/numerosity). Because the data had shown strong accuracy biases (see [Supplementary Material](#)), we also reported Weber fraction (WF, std/mean response), a bias-free measures of sensory precision. The calculation formulas for CoV and WF were as below Formula (1) and (2) (n : numerosity level; K : the total number of trials of the particular numerosity level

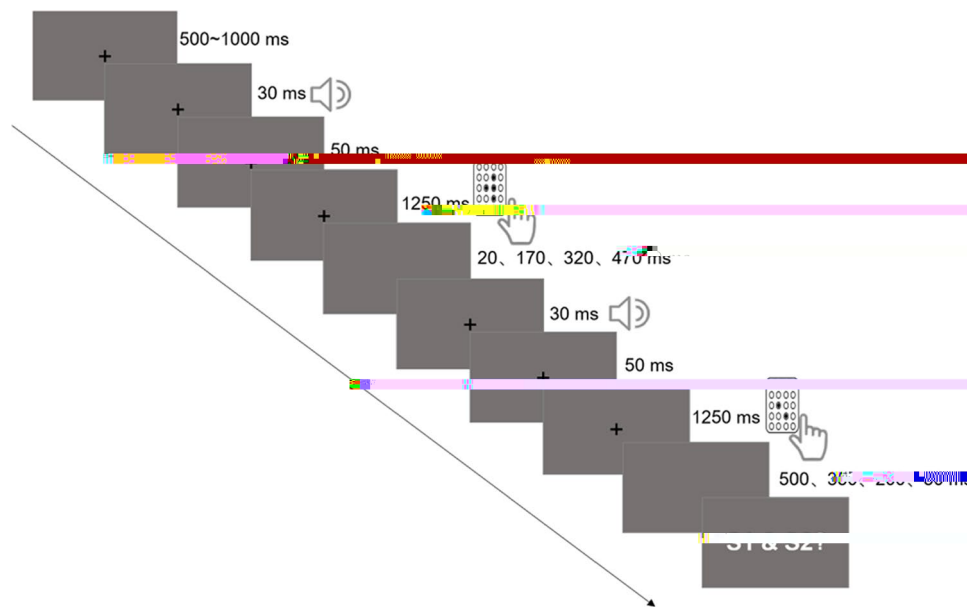


Fig. 2 Double enumeration paradigm in Experiment 2. The interstimulus intervals (ISIs) between two tactile stimuli composed of three segments: the blank followed the first tactile pins array (different in Experiment 2a–2d: 2a: 20 ms; 2b: 170 ms; 2c: 320 ms; 2d: 470 ms), the alarming sound (70 Hz, 30 ms) and the fixation before the second array (50 ms). In this case, there were four levels of ISI in Experiment 2. At the same time, there were four different durations

of the blank before the questions that prompted the participants to respond: 500 ms (2a), 350 ms (2b), 200 ms (2c), and 50 ms (2d) to ensure that the total duration of each trial in the four sub-experiments was consistent. At the end of each trial, the participants were asked to report the numbers of the first array (S1) and the second array (S2) of tactile pins by pressing the corresponding keys.

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

$$CoV(n) = \frac{\sqrt{\frac{1}{K} \sum_{j=1}^K \left(R_{n,j} - \frac{1}{K} \sum_{j=1}^K R_{n,j} \right)^2}}{n} \quad (1)$$

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

CoV and WF were first calculated at each numerosity level (1–8), and then averaged them at 1, 2, 3 and 6, 7, 8 for subitizing range and estimation range respectively.

Error Rate We adopted a 2 (numerical range of S1: subitizing vs estimation) \times 2 (numerical range of S2: subitizing vs estimation) \times 4 (ISI: 100 ms, 250 ms, 400 ms, and 550 ms) repeated-measured ANOVA test on ERR of reporting S2. There was a significant three-way interaction on ERR ($F_{(2.262, 56.553)} = 10.19, p < .001, \eta^2_p = .29$). Simple effect analysis revealed that significant two-way interaction ($F_{(1, 25)} = 16.65, p < .001, \eta^2_p = .40$) between S1 and S2 occurred only when ISI was 100 ms (see Fig. 3A, from left to right in each panel were the results of Experiment 2a, 2b, 2c, and 2d).

Further analysis showed that, compared to the S–S condition ($M = .24, SE = .04$), in the E–S condition ($M = .34, SE = .04$) the ERR of S2 was larger ($F_{(1, 25)} = 25.46, p < .001, \eta^2_p = .50$). Correspondingly, the ERR of the S–E condition ($M = .78, SE = .03$) was also larger than that of the E–E condition ($M = .69, SE = .04, F_{(1, 25)} = 8.60, p = .007, \eta^2_p = .26$). In brief, when ISI was 100 ms, switching between different enumeration processes caused more errors in enumerating S2, regardless of the numerical condition of S2. This switch cost effect on ERR disappeared with the increase of ISI. Additionally, the results revealed a main effect of the numerical range of S1 ($F_{(1, 25)} = 6.07, p = .021, \eta^2_p = .19$). Compared with S1 in the subitizing range ($M = .50, SE = .03$), when the S1 was within the estimation range ($M = .52, SE = .03$) the ERR of S2 raised. The main effect of the numerical range of S2 was also significant ($F_{(1, 25)} = 294.97, p < .001, \eta^2_p = .92$), suggesting participants made more mistakes when they reported S2 in the estimation range ($M = .76, SE = .03$) relative to the subitizing range ($M = .26, SE = .03$).

To inspect the magnitude of switch cost caused by switching between subitizing and estimation, we defined the switch cost from estimation to subitizing as $Err_{est-sub} - Err_{sub-sub}$ and the switch cost from subitizing to estimation as $Err_{sub-est} - Err_{est-est}$ (the larger the magnitude of ERR, the greater of the costs caused by the switching between subitizing and estimation). Then, we compared two kinds of switch cost

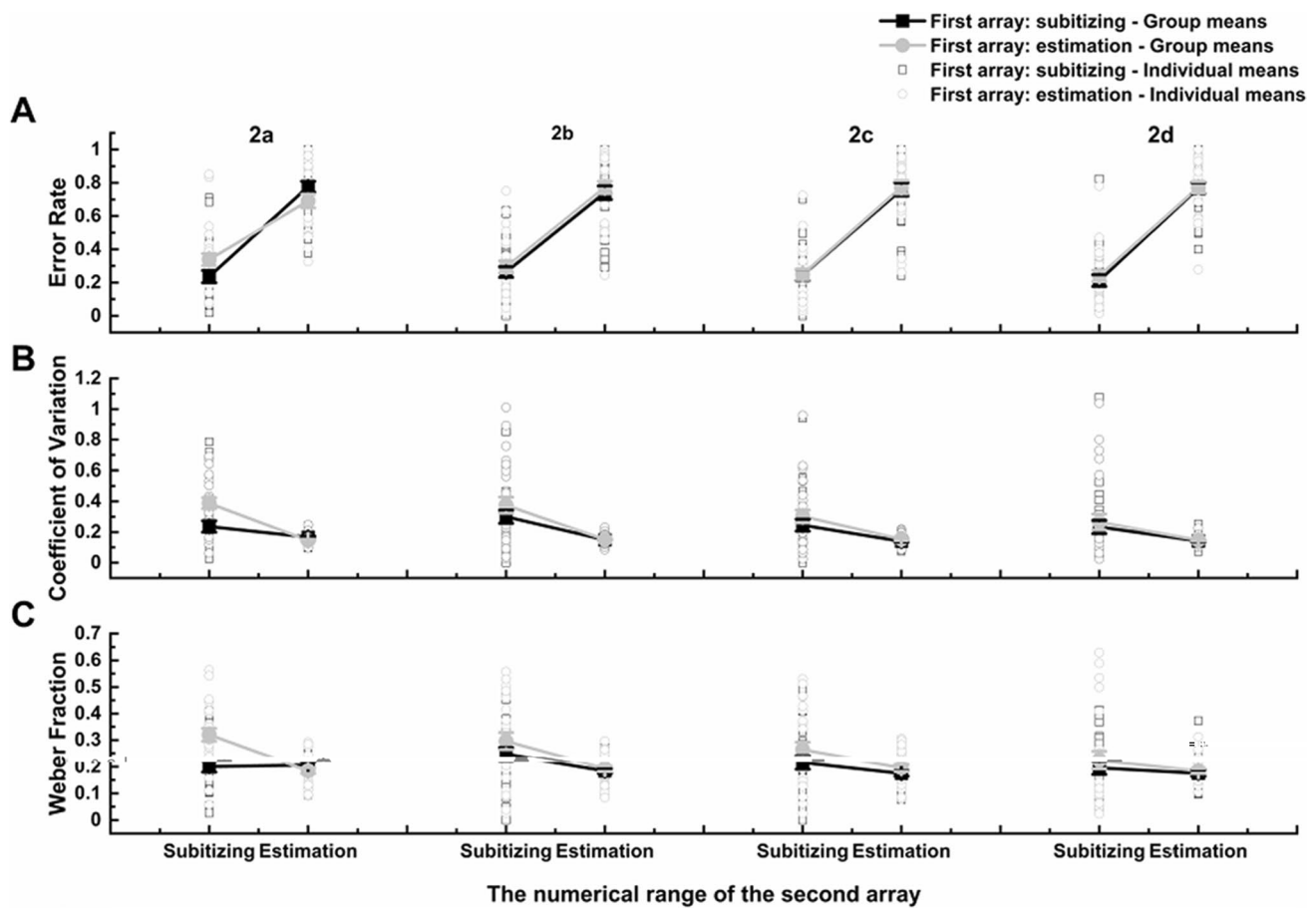


Fig. 3 Results of Experiment 2. These three panels showed the group and individual means of the participants' performance on the second enumeration task, including Error Rate (**A**), Coefficient of variation (**B**) and Weber Fraction (**C**). From left to right in each panel were the results of Experiment 2a, 2b, 2c, and 2d. Black curves and square

represented the conditions whose numerical range of the first array were within subitizing. Gray curves and circle represented the conditions whose numerical range of the first array were within estimation. Error bars denoted the standard errors.

with a paired-*t* test (see Fig. 4A) and found that there was no significant difference ($t(25) = .733$, $p = .47$) between the switch from estimation to subitizing ($M = .10$, $SE = .02$) and the switch in the opposite direction ($M = .09$, $SE = .03$). As mentioned above, error rate has some limitations for its sensitivity in measuring the effect size, so we also analyzed the CoV and WF.

Coefficient of Variation Repeated-measured ANOVA of 2 (numerical range of S1) \times 2 (numerical range of S2) \times 4 (ISI) on CoV displayed a significant three-way interaction ($F_{(3, 75)} = 4.01$, $p = .011$, $\eta^2_p = .14$; see Fig. 3B). Simple analysis showed that the two-way interaction between the numerical range of S1 and S2 were both significant in Experiment 2a ($F_{(1, 25)} = 22.85$, $p < .001$, $\eta^2_p = .48$) and 2b ($F_{(1, 25)} = 5.73$, $p = .025$, $\eta^2_p = .17$). Further analysis showed that in Experiment 2a when the numerical range of S2 was within subitizing range, precision descended significantly ($F_{(1, 25)} = 20.53$, $p < .001$, $\eta^2_p = .49$) in the E-S condition (M

$= .39$, $SE = .04$), compared with the S-S condition ($M = .24$, $SE = .04$). At the same time, when the numerical range of S2 was within estimation range, there was also a significant ($F_{(1, 25)} = 5.96$, $p = .022$, $\eta^2_p = .33$) precision reduction in the S-E condition ($M = .17$, $SE = .01$) related to the E-E condition ($M = .15$, $SE = .01$). Additionally, further analysis in Experiment 2b suggested that there was an asymmetric switch effect. Specifically, when the numerical range of S2 was within subitizing range, a significant precision reduction ($F_{(1, 25)} = 5.91$, $p = .023$, $\eta^2_p = .18$) was found for the E-S condition ($M = .38$, $SE = .05$) compared to the S-S condition ($M = .30$, $SE = .04$). However, when the numerical range of S2 was within estimation range, there was no significant difference between the S-E and the E-E conditions ($F_{(1, 25)} = .39$, $p = .539$).

In addition, the paired-*t* test of the magnitude of switch cost suggested that in both Experiment 2a or 2b (see Fig. 4B and 4D), the switch from estimation to subitizing (Exp. 2a: $M = .15$, $SE = .03$; Exp. 2b: $M = .08$, $SE = .03$) generated a larger cost than the switch in the opposite direction (Exp. 2a:

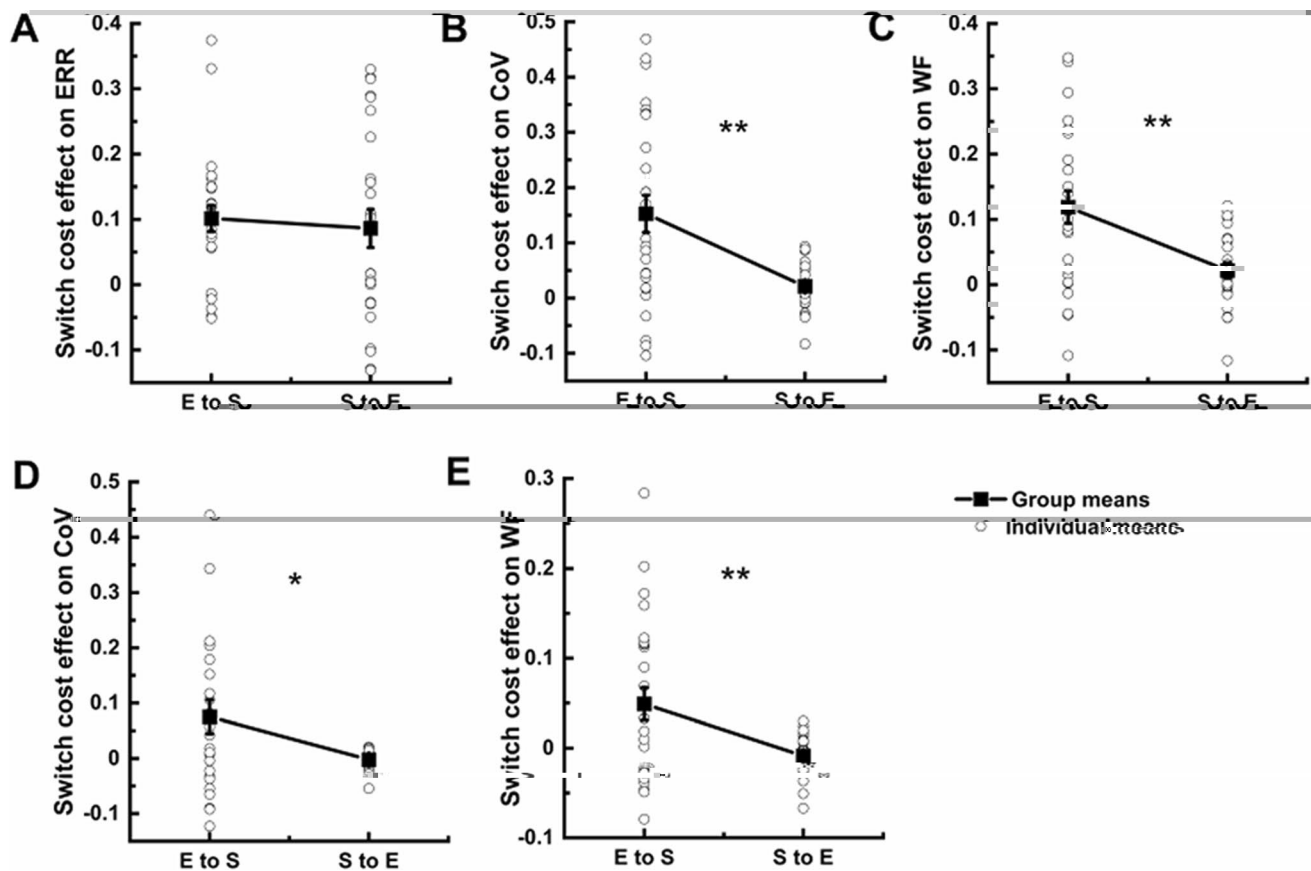


Fig. 4 The switch cost effect of Experiment 2a and Experiment 2b. The switch cost effects were defined as the differences between the switch condition and the no-switch condition on Error Rate (**A**), Coefficient of variation (**B**), and Weber Fraction (**C**) of Experiment 2a, and on Coefficient of variation (**D**) and Weber Fraction (**E**) of

Experiment 2b respectively. “E to S” meant the switch cost from estimation to subitizing and “S to E” meant the switch cost from subitizing to estimation. Black curve and circle represented group means and individual data respectively. * $p < .05$, ** $p < .01$. Error bars were standard errors.

$M = .02$, $SE = .01$; Exp. 2b: $M = -.002$, $SE = .003$), showing an asymmetry in switch cost between subitizing and estimation (Exp. 2a: $t(25) = 3.96$, $p = .001$, Cohen’s $d = 1.05$; Exp. 2b: $t(25) = 2.44$, $p = .02$, Cohen’s $d = .69$). In other words, there was a greater switch cost when S2 was in the subitizing range.

Furthermore, the Repeated-measured ANOVA of 2 (numerical range of S1) \times 2 (numerical range of S2) \times 4 (ISI) applied on CoV displayed a significant main effect of S1 range ($F_{(1, 25)} = 20.94$, $p < .001$, $\eta^2_p = .46$). Compared with S1 in the subitizing range ($M = .20$, $SE = .02$), when the S1 was within the estimation range ($M = .24$, $SE = .02$) the CoV of S2 increased, indicating a reduction in the precision. The main effect of the S2 range was also significant ($F_{(1, 25)} = 18.07$, $p < .001$, $\eta^2_p = .42$). There was a higher precision when S2 was within the estimation range ($M = .15$, $SE = .01$) instead of the subitizing range ($M = .29$, $SE = .04$), suggesting that subitizing rather than estimation was more likely affected by the first enumeration task. When the second array of tactile pins was presented, enumeration task 1

was still going on and would deprive part of the attentional resources. According to the “dual component hypothesis” that subitizing rather than estimation relied more on attentional resources, the lack of attentional resources would have a greater impact on the performance of the subitizing. Specifically, the CoV in subitizing range was larger than its counterpart in estimation range. This result was in line with the previous studies using dual task paradigm to manipulate the attentional resources for enumeration task in tactile and visual modalities (Burr et al., 2010; Tian & Chen, 2018; Vetter et al., 2008). Under dual task conditions, the precision of subitizing rather than estimation was more vulnerable. All these results indicated that subitizing relied greater on attentional resources than estimation, which is consistent with the “dual component hypothesis”. The main effect of ISI was significant ($F_{(3, 75)} = 4.38$, $p = .007$, $\eta^2_p = .15$). Post hoc analysis showed that there was significant difference ($p = .049$) between experiment 2b (ISI = 250 ms, $M = .24$, $SE = .03$) and 2d (ISI = 550 ms, $M = .20$, $SE = .02$). With the increase of ISI, the attentional resources deprived by task

1 gradually recovered, resulting in an improvement in the precision of task 2.

Weber Fraction The same 2 (numerical range of S1) \times 2 (numerical range of S2) \times 4 (ISI) repeated-measured ANOVA test was also applied on WF of S2. It was similar to the result of CoV. The result showed that there was also a significant three-way interaction ($F_{(3, 75)} = 4.96$, $p = .003$, $\eta^2_p = .17$; see Fig. 3C). Simple analysis showed that the two-way interactions between the numerical range of S1 and S2 were both significant in Experiment 2a ($F_{(1, 25)} = 22.81$, $p < .001$, $\eta^2_p = .48$) and 2b ($F_{(1, 25)} = 4.78$, $p = .038$, $\eta^2_p = .14$). Further analysis showed that in Experiment 2a when the numerical range of S2 was within subitizing, a significant precision reduction ($F_{(1, 25)} = 23.01$, $p < .001$, $\eta^2_p = .47$) was found for the E-S condition ($M = .32$, $SE = .02$), compared with the S-S condition ($M = .20$, $SE = .02$). However, there was no significant difference ($F_{(1, 25)} = 3.49$, $p = .074$, $\eta^2_p = .20$) between the S-E and the E-E conditions. We found the same results in Experiment 2b. Specifically, when the numerical range of S2 was within subitizing, a significant precision reduction ($F_{(1, 25)} = 7.27$, $p = .012$, $\eta^2_p = .21$) was found in the E-S condition ($M = .30$, $SE = .03$) compared to the S-S condition ($M = .25$, $SE = .03$). When the numerical range of S2 was within estimation, there was no significant difference between the S-E and the E-E conditions ($F_{(1, 25)} = 3.28$, $p = .082$).

We also analyzed the magnitude of switch cost (see Fig. 4C and Fig. 4E), the results of paired-t test suggested that the switch from estimation to subitizing ($WF_{\text{sub-est}} - WF_{\text{est-est}}$, Exp. 2a: $M = .12$, $SE = .02$; Exp. 2b: $M = .05$, $SE = .02$) generated a larger cost than the switch in the opposite direction ($WF_{\text{est-sub}} - WF_{\text{sub-sub}}$, Exp. 2a: $M = .02$, $SE = .01$; Exp. 2b: $M = -.008$, $SE = .005$), showing the asymmetry in switch cost between subitizing and estimation (Exp. 2a: $t(25) = 3.86$, $p = .001$, Cohen's $d = 0.98$; Exp. 2b: $t(25) = 3.01$, $p = .006$, Cohen's $d = 0.85$), in Experiment 2a and 2b. This result pattern was consensus with the one in CoV.

In addition, the repeated-measured ANOVA of 2 (numerical range of S1) \times 2 (numerical range of S2) \times 4 (ISI) applied on WF also displayed a significant main effect of S1 range ($F_{(1, 25)} = 24.81$, $p < .001$, $\eta^2_p = .498$). Compared with S1 in the subitizing range ($M = .20$, $SE = .01$), when the S1 was within the estimation range ($M = .23$, $SE = .02$) the WF of S2 was raised. At the same time, the main effect of the S2 range was also significant ($F_{(1, 25)} = 14.211$, $p = .001$, $\eta^2_p = .36$). There was a higher precision when S2 was within the estimation range ($M = .19$, $SE = .01$) instead of the subitizing range ($M = .25$, $SE = .02$). The main effect of ISI was significant ($F_{(3, 75)} = 4.40$, $p = .007$, $\eta^2_p = .15$), indicating an improvement in the precision with the increase of ISI. Post hoc analysis showed that there was significant difference

($p = .002$) only between experiment 2a (ISI = 250 ms, $M = .23$, $SE = .01$) and 2d (ISI = 550 ms, $M = .20$, $SE = .02$).

To sum up, we found significant switch effects on all dependent variables, when ISI was 100 ms. Importantly, the switch effects were asymmetric on CoV and WF. However, there was no significant interaction on any dependent variable in any of Experiment 2b, 2c, or 2d, except for CoV and WF of 2b, indicating a lack of switch cost when ISI was 400 ms, or 550 ms. Task-set reconfiguration could explain the absence of switch cost, that participants obtained sufficient time to recover the attentional resources consumed by reconstruction process in the switch condition when ISIs were long enough.

Experiment 3

We detected an asymmetric switch cost when ISIs were 100 ms in Experiment 2. As mentioned above, changes in numerosity are always accompanied by changes in non-numerical properties of stimuli. To exclude the potentially alternative account that the results of the S-E and E-S conditions, could be contaminated (or contributed) by the task-irrelevant physical change in non-numerical properties of stimuli, rather than the task relevant process (i.e., switch between subitizing and estimation), we conducted Experiment 3 to serve as a control for Experiment 2.

Method

The design of Experiment 3 was the same as Experiment 2a except that participants were only required to conduct one task, reporting S1 (single task 1) or S2 (single task 2). Thus, we kept the same sample size ($N = 26$; 10 males; mean age 21.3 ± 0.39) of Experiment 2. Participants were instructed to report either S1 or S2 at the beginning of each block and their reporting orders were counterbalanced. Still, participants completed a baseline task at the beginning of Experiment 3 as in Experiment 2. All participants gave their informed consent at the beginning of the experiment.

Results and Discussion

In Experiment 2a, except for the numerical properties of the second array, there were several factors may also contribute to the performance of the enumeration of S2 (denoted here as E2), including: (a) the mere exposure to the non-numerical properties of the first array (P1), (b) the mere exposure to the second array (P2), and (c) the potential extra cost of the numerical processing from the first array to the second array that was specifically based on the numerical relationship of their numerosity ranges (denoted as $N1 \blacktriangle N2$, a switch or

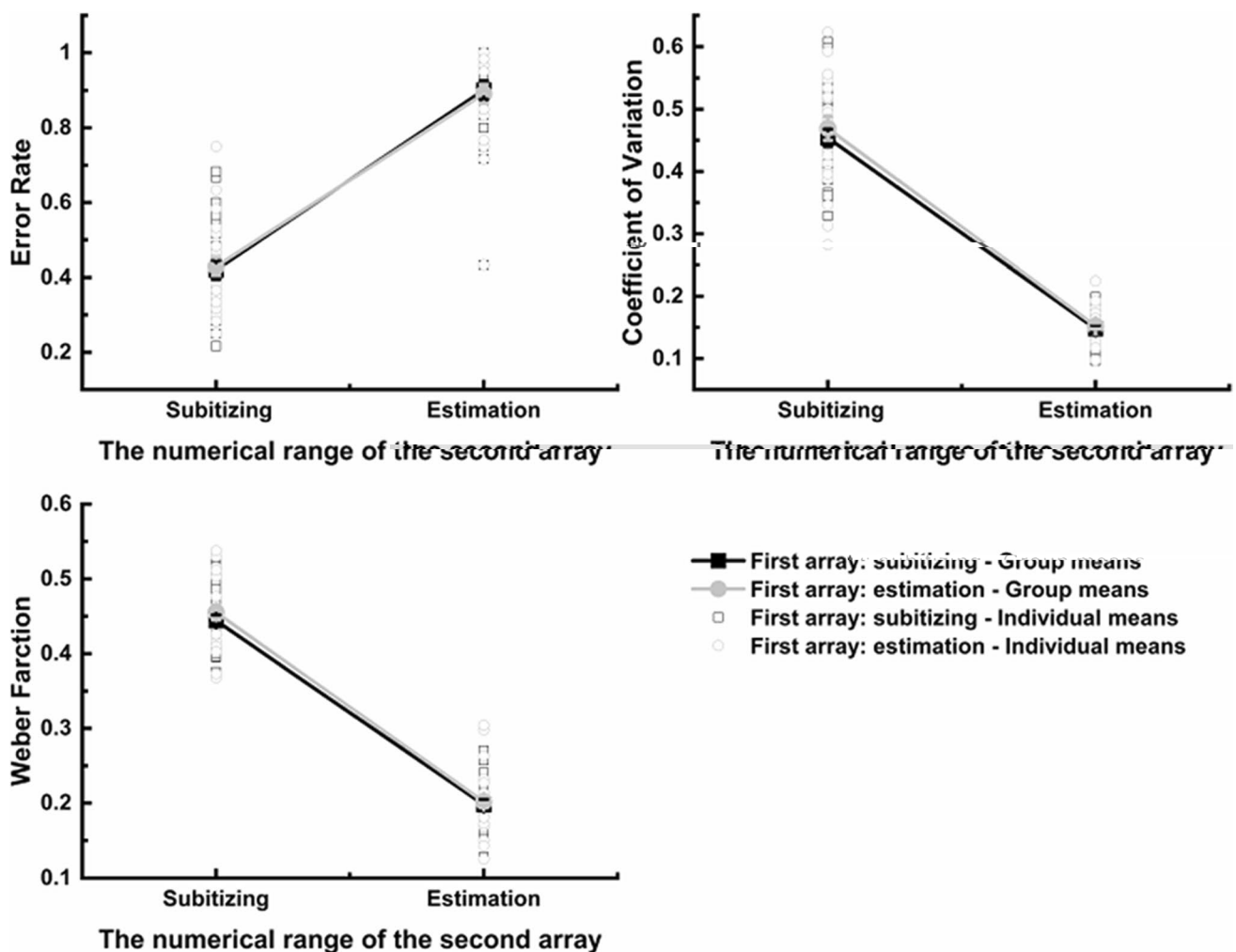


Fig. 5 The results of Experiment 3. The figure showed the group and individual means of the participants' performance on single task 2 including the Error Rate (A), Coefficient of variation (B), and Weber Fraction (C). Other aspects of the figure format were similar to Fig. 3.

no switch across subitizing and estimation processes). The E2 received influences from all above 3 factors ($E2 = P1 + P2 + N1 \blacktriangle N2$). However, the performance of the single task 2 in Experiment 3 (denoted here as E3), in which the first array should be ignored without further numerical processing, received influences from only 2 factors ($E3 = P1 + P2$). In this case, we believed that if there was no switch cost effect in single task 2 of Experiment 3, the change in non-numerical properties of stimuli couldn't account for the results of Experiment 2. Therefore, here we also focused on the performance of single task 2. We adopted a repeated-measured ANOVA test with S1 range and S2 range as independent variables on ERR, CoV and WF.

The results showed that the main effect of the S2 range was significant on all dependent variables (ERR: $F_{(1, 25)} = 321.31, p < .001, \eta^2_p = .93$; CoV: $F_{(1, 25)} = 356.84, p < .001, \eta^2_p = .94$; WF: $F_{(1, 25)} = 557.94, p < .001, \eta^2_p = .96$). Compared with S2 in the estimation range (ERR: $M = .90, SE$

$= .02$; CoV: $M = .15, SE = .01$; WF: $M = .20, SE = .01$), participants' responses for S2 in the subitizing range had fewer mistakes ($M = .42, SE = .02$), and a larger CoV ($M = .46, SE = .02$) and WF ($M = .45, SE = .01$) (see Fig. 5). The results suggested that the mere exposure to the non-numerical properties of the first array could also capture some attentional resources and influenced the precision of task 2. Importantly, the results revealed no significant interaction on any dependent variable, indicating an absence of switch cost when participants reported only one of the stimuli and no perceptual processes switch was needed. This confirmed that differences between non-numerical properties of tactile stimuli were not able to explain the asymmetric switch cost in Experiment 2a.

Cross-experiment analysis between Experiment 2a and Experiment 3 We applied a 2 (numerical range of S1) \times 2 (numerical range of S2) \times 2 (task type: dual-task in Experiment 2a and single task in Experiment 3) repeated-measured

ANOVA test for data combined across Experiment 2a and Experiment 3. There was a significant three-way interaction on ERR ($F_{(1, 50)} = 12.42, p = .001, \eta^2_p = .20$), CoV ($F_{(1, 50)} = 19.08, p < .001, \eta^2_p = .28$) and WF ($F_{(1, 50)} = 19.53, p < .001, \eta^2_p = .28$). Simple effect analysis indicated a significant interaction between S1 and S2 only in the dual-task on ERR ($F_{(1, 50)} = 30.82, p < .001, \eta^2_p = .38$), CoV ($F_{(1, 50)} = 43.26, p < .001, \eta^2_p = .47$) and WF ($F_{(1, 50)} = 42.77, p < .001, \eta^2_p = .46$), demonstrating that a significant switch cost occurred only in dual-tasks. Further analysis revealed that the ERR, CoV and WF in the switch condition were significantly greater than those in the no-switch condition, which were consistent with the results of Experiment 2. Specifically, ERR, CoV and WF of the E-S condition (ERR: $F_{(1, 51)} = 35.98, p < .001, \eta^2_p = .41, M = .34, SE = .03$; CoV: $F_{(1, 51)} = 39.19, p < .001, \eta^2_p = .43, M = .39, SE = .03$; WF: $F_{(1, 51)} = 44.67, p < .001, \eta^2_p = .46, M = .32, SE = .02$) were greater than those of the S-S condition (ERR: $M = .24, SE = .03$; CoV: $M = .24, SE = .03$; WF: $M = .20, SE = .02$). At the same time, compared to the E-E condition (ERR: $M = .70, SE = .03$; CoV: $M = .15, SE = .01$; WF: $M = .19, SE = .01$), ERR, CoV and WF of the S-E condition (ERR: $F_{(1, 51)} = 16.04, p < .001, \eta^2_p = .24, M = .78, SE = .03$; CoV: $F_{(1, 51)} = 10.03, p = .002, \eta^2_p = .25, M = .17, SE = .01$; WF: $F_{(1, 51)} = 5.66, p = .021, \eta^2_p = .14, M = .21, SE = .01$) were also greater.

The main effects of task type were all significant on ERR ($F_{(1, 50)} = 15.61, p < .001, \eta^2_p = .24$), CoV ($F_{(1, 50)} = 13.73, p = .001, \eta^2_p = .22$) and WF ($F_{(1, 50)} = 47.461, p < .001, \eta^2_p = .49$), indicating there were fewer mistakes and higher precisions in dual-task (ERR: $M = .51, SE = .03$; CoV: $M = .23, SE = .01$; WF: $M = .23, SE = .01$) than in single task (ERR: $M = .66, SE = .03$; CoV: $M = .31, SE = .01$; WF: $M = .33, SE = .01$). Given the ERR ($F_{(1, 50)} = 3.33, p = .074, \eta^2_p = .06$), CoV ($F_{(1, 50)} = 1.06, p = .30, \eta^2_p = .02$) and WF ($F_{(1, 50)} = 1.06, p = .31, \eta^2_p = .02$) in the baseline of the dual-task group and the single-task group were not significantly different, we proposed that the practicing effect contributed to the better performance in dual-task on ERR, CoV and WF. Participants in Experiment 2 enumerated 2560 times (320 trials \times 2 tasks in each trial \times 4 sub-experiments) while participants in Experiment 3 enumerated 640 times (320 trials \times 2 single tasks). Therefore, participants got more chances to practice in Experiment 2.

To identify the potential practicing effect in Experiment 2, we encoded four sub-experiments in Experiment 2 according to their completed orders as four time bins: T1, T2, T3, and T4. T1 was the first to complete and T4 was the last to complete. We applied a 2 (numerical range of S1) \times 2 (numerical range of S2) \times 2 (time: T1 and T4) repeated-measured ANOVA test on ERR, CoV and WF. The results revealed a significant main effect of time on ERR ($F_{(1, 25)} = 11.33, p = .002, \eta^2_p = .31$), CoV ($F_{(1, 25)} = 14.51, p = .001, \eta^2_p = .37$) and WF ($F_{(1, 25)} = 8.46, p = .008, \eta^2_p = .25$),

implying that there was indeed a practice effect. Specifically, compared to T1 (ERR: $M = .54, SE = .03$; CoV: $M = .25, SE = .02$; WF: $M = .24, SE = .01$), participants made fewer errors and had higher precisions in T4 (ERR: $M = .49, SE = .03$; CoV: $M = .19, SE = .02$; WF: $M = .20, SE = .02$). We then tested whether ERR, CoV and WF were different between Experiment 2a in T1 (T1_100) and Experiment 3. Because their total samples were largely different, we used the bootstrapping method (bootstrap sample was 1000). The results showed that there was no difference between T1_100 and Experiment 3 on ERR, CoV and WF except for the S-E condition on ERR ($p = .044$), and the S-S condition on WF ($p = .018$). These results supported that practicing indeed improved performance in dual-task.

Some might attribute the interaction between S1 and S2 in Experiment 2a to an asymmetric practicing effect. Specifically, the practicing effect in the no-switch condition (E-E and S-S conditions) could be bigger than that in the switch condition (E-S and S-E conditions). However, this alternative account seemed not possible. First, if the interaction between S1 and S2 was caused by the asymmetric practicing effect, compared to T1, the asymmetric practicing effect could accumulate and reach a maximum at T4, leading to a more significant interaction between S1 and S2. However, we failed to find a significant time \times S1 \times S2 three-way interaction (ERR: $F_{(1, 25)} = .76, p = .393$; CoV: $F_{(1, 25)} = .01, p = .937$; WF: $F_{(1, 25)} = .03, p = .871$). Second, the asymmetric practicing effect should not only appear in Experiment 2a but also in other sub-experiments, since the sub-experiment orders were randomized. Still, some might think that the ISIs were longer in other sub-experiments, so perhaps the asymmetric practicing effect only occur when ISI was short. However, we did not find a significant time \times S1 \times S2 three-way interaction in trials of experiment 2a in T1 and T4 yet (ERR: $F_{(1, 12)} = 3.51, p = .09$; CoV: $F_{(1, 12)} = .67, p = .43$; WF: $F_{(1, 25)} = .71, p = .42$). Thus, we excluded the possibility that asymmetric switch cost in Experiment 2a was attributed to asymmetric practicing effect or the changes in non-numerical properties of stimuli, followed by changes in numerosity.

General Discussion

The relationship between the underlying mechanisms of subitizing and estimation is still debated. We explored their relationship in tactile modality. Using a double enumeration paradigm, we found a significant asymmetric switch cost effect that decreased with the expanding of the time intervals between the two consecutively tactile arrays. A typical switch cost occurred in Experiment 2a (ISI = 100 ms). Compared to the no-switch condition (S-S and E-E), the error rate of the second enumeration increased while the precision reduced when the enumeration process switched between subitizing and estimation

(E-S and S-E). This finding was in line with previous studies that used task-switching paradigm (Meiran, 1996; Monsell, 2003; Rogers & Monsell, 1995). These studies asked participants to switch between two or more kinds of tasks and also found that there were longer response times and higher error rate in task-switching trials than in task-repeating trials. Thus, the findings from Experiment 2a indicated that tactile subitizing and estimation utilized different perceptual mechanisms.

Moreover, both CoV and WF manifested an asymmetric switch cost effect. Compared to subitizing switched to estimation, when estimation switched to subitizing, the switch cost effect was more robust with larger magnitudes. The asymmetry embedded in switch cost effect corresponded well with “dual component hypothesis”. The hypothesis suggested that subitizing reflected the operation of OI, which owned a very limited capacity of about four items (Burr et al., 2010). OI system might sit on top of the numerosity-estimation system, supporting rather than replacing estimation/ANS for low numbers (Anobile, Cicchini et al., 2016). Accordingly, subitizing could trigger both the ANS and the OI processes while estimation only activated the ANS. In this case, switching from subitizing to estimation triggered no new component yet switching from estimation to subitizing must call on OI additionally. As a result, when estimation switched to subitizing, the consumption of attentional resources was greater than the other way around. This functionally differential switches brought forth an asymmetric effect.

Our results supported neither “single estimation component hypothesis” nor “single object-individuation component hypothesis”. The “single estimation component hypothesis” considers subitizing and estimation as the same process and predicts a lack of switch cost effect in our experiments. The switch cost effect, however, was observed in Experiment 2a and Experiment 2b and disproved this “single estimation component hypothesis”. Especially in Experiment 2a, the switch cost effect displayed its asymmetry which contradicts with the “single object-individuation component hypothesis”. “Single object-individuation component hypothesis” supposes that that subitizing and estimation relies on OI and ANS separately. Compared with the no-switch condition (E-E and S-S), when the enumeration process switched between subitizing and estimation, it would give rise to the switch between OI and ANS, then there would be a switch cost. However, the attentional resources consumption caused by ANS (estimation) switching to OI (subitizing) should be the same as the other way around. In other words, the switch cost should be symmetric, which was inconsistent with our results - an asymmetric switch cost. Consequently, our results disproved “single estimation component hypothesis” and “single object-individuation component hypothesis”, but supported of “dual component hypothesis”.

Note that in Experiment 2, we only found switch cost within a narrow temporal range - the first numerical processing significantly influenced the second numerical processing when ISI between the two events was 100 ms (Experiment 2a). When ISI increased to 250 ms, the switch cost effect was only found on precision indexes. And increasing ISI to 400 ms (Experiment 2c) or 550 ms (Experiment 2d) resulted in the absence of the switch cost effect. The absence of the switch costs with extended ISIs could be accounted for by the preparation effect, in the framework of task-set reconfiguration theory. Task-set reconfiguration theory assumes that the additional attentional resources expenditure during task-set reconstructed results in switch cost (Logan & Gordon, 2001; Mayr & Kliegl, 2000; Monsell & Mizon, 2006). Therefore, in the present study, when there was enough time interval between two tasks, additional attentional resources expenditure could recover, and the switch cost effect decreased accordingly (Arrington & Logan, 2004; Rogers & Monsell, 1995).

Moreover, in our study, the results of Experiment 3 showed that the asymmetric switch cost were indeed caused by the numerosity of stimuli rather than the non-numerical properties of stimuli. This result suggested that the ability to perceive numerosity was innate but not acquired by learning the correlations between other magnitudes, such as density and area. This innate number sense is consistent with the “number sense theory” (Arrighi et al., 2014; Burr & Ross, 2008; Cicchini et al., 2016) which proposes that numerosity of stimuli is a primary perceptual attribute like color. Recent studies confirmed this view. In an EEG study, Park et al. (2016) used a novel analytic method to test the contributions of numerical and non-numerical attributes during numerosity processing. The results did indicate that participants were more sensitive to changes in numerosity rather than changes in other non-numerical properties of stimuli. Moreover, adaptation and serial dependence (an attractive bias making a current stimulus to appear more similar to previous ones) are two characteristics shared by all primary attributes, such as, orientation (Blakemore & Campbell, 1969; Fischer & Whitney, 2014). Extensive studies suggested that numerosity perception was also susceptible to adaptation (Anobile, Arrighi, et al., 2016a; Anobile, Cicchini, & Burr, 2016b; Burr et al., 2018; Togoli et al., 2021) and serial dependence (Fornaciai & Park, 2018, 2020). Taken together, these studies provide the evidence for the view that numerosity of stimuli is a primary perceptual attribute.

In addition, the “number sense theory” assumes that at some stage of encoding, numerosity becomes independent of perceptual characteristics such as sensory modality or presentation format (Anobile et al., 2021; Burr et al., 2018). Consistent with the theory, studies using adaptation paradigm showed that the non-symbolic number representation was independent of sensory modality

or presentation format (Anobile, Arrighi, et al., 2016a; Togoli & Arrighi, 2021). Previous studies suggested that tactile objects recognition could evoke representations in a posterior inferior temporal region of visual extra striate cortex, which was similar to the representations evoked by visual recognition of the same objects (Pietrini et al., 2004). Recently, behavioral studies further suggested that numerosity information was automatically coded in in external, real-world, coordinates both in visual and tactile modality (Togoli et al., 2021). All of these investigations indicated that there might be a supramodal non-symbolic number representation system to code numerosity information from different modalities.

Recent studies used human brain imaging technique suggested that this abstract, modality- and format-independent number representation system could reside within IPS and prefrontal cortex (PFC). IPS and PFC receive the input from many senses, including visual, auditory and tactile modalities. They are the hub of cross-modality information summary (Nieder, 2017). In recent years, fMRI and electrophysiological studies have both found that IPS and PFC played an important role in cross-modal number coding (Eger et al., 2003; Nieder, 2012; Piazza et al., 2006). For example, electrophysiological studies in monkey found that neurons in ventral intraparietal area (VIP) and lateral prefrontal cortex (LPFC) encoded numbers, no matter whether numbers were presented as auditory pulses, visual items, or both (Nieder, 2012). All of these studies supported that IPS and PFC were the hub for nonverbal, supramodal neuronal coding of numerical quantity.

To sum up, our results showed an asymmetric switch cost within a narrow temporal range: the first numerical processing significantly influenced the second numerical processing when ISI between the two events was 100 ms. Specifically, the error rate of the second enumeration increased, while the precision decreased when the enumeration process switched between subitizing and estimation (S-E and E-S), relative to the no switch condition (E-E and S-S). What's more, an asymmetry was observed on the precision. Compared to switching from subitizing to estimation, switching from estimation to subitizing induced a robust and larger switch cost effect. The relationship between subitizing and estimation in tactile modality accorded closely with the “dual component hypothesis” as revealed in visual modality. This consistency indicated that the representation of non-symbolic number was abstract and supramodal.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12144-022-02858-w>.

Acknowledgements This work was supported by grants from the Natural Science Foundation of China (Grant No. 62061136001, 31861133012, 11774379).

Funding This study was funded by Natural Science Foundation of China (Grant No. 62061136001, 31861133012, 11774379).

Data Availability All data are available at <https://osf.io/ksjcu/>.

Declarations

Ethics Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standard

Conflicts of Interest The authors declare that they have no conflict of interest.

Informed Consent Informed consent was obtained from all individual participants included in the study.

References

- Amedi, A. (2002). Convergence of Visual and Tactile Shape Processing in the Human Lateral Occipital Complex. *Cerebral Cortex*, 12(11), 1202–1212. <https://doi.org/10.1093/cercor/12.11.1202>
- Amedi, A., Malach, R., Hendler, T., Peled, S., & Zohary, E. (2001). Visuo-haptic object-related activation in the ventral visual pathway. *Nature Neuroscience*, 4(3), 324–330. <https://doi.org/10.1038/85201>
- Anobile, G., Arrighi, R., & Burr, D. C. (2019). Simultaneous and sequential subitizing are separate systems, and neither predicts math abilities. *Journal of Experimental Child Psychology*, 178, 86–103. <https://doi.org/10.1016/j.jecp.2018.09.017>
- Anobile, G., Arrighi, R., Castaldi, E., & Burr, D. C. (2021). A Sensorimotor Numerosity System. *Trends in Cognitive Sciences*, 25(1), 24–36. <https://doi.org/10.1016/j.tics.2020.10.009>
- Anobile, G., Arrighi, R., Togoli, I., & Burr, D. C. (2016a). A shared numerical representation for action and perception. *eLife*, 5, e16161. <https://doi.org/10.7554/eLife.16161>
- Anobile, G., Cicchini, G. M., & Burr, D. C. (2016b). Number As a Pri-

- Burr, D. C., Anobile, G., & Arrighi, R. (2018). Psychophysical evidence for the number sense. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 373(1740), 20170045. <https://doi.org/10.1098/rstb.2017.0045>
- Burr, D., & Ross, J. (2008). A Visual Sense of Number. *Current Biology*, 18(6), 425–428. <https://doi.org/10.1016/j.cub.2008.02.052>
- Burr, D. C., Turi, M., & Anobile, G. (2010). Subitizing but not estimation of numerosity requires attentional resources. *Journal of Vision*, 10(6), 20–20. <https://doi.org/10.1167/10.6.20>
- Cai, Y., Hofstetter, S., van Dijk, J., Zuiderbaan, W., van der Zwaag, W., Harvey, B. M., & Dumoulin, S. O. (2021). Topographic numerosity maps cover subitizing and estimation ranges. *Nature Communications*, 12(1), 3374. <https://doi.org/10.1038/s41467-021-23785-7>
- Cheng, X., Lin, C., Lou, C., Zhang, W., Han, Y., Ding, X., & Fan, Z. (2021). Small numerosity advantage for sequential enumeration on RSVP stimuli: An object individuation-based account. *Psychological Research*, 85(2), 734–763. <https://doi.org/10.1007/s00426-019-01264-5>
- Chesney, D. L., & Haladjian, H. H. (2011). Evidence for a shared mechanism used in multiple-object tracking and subitizing. *Attention Perception & Psychophysics*, 73(8), 2457–2480. <https://doi.org/10.3758/s13414-011-0204-9>
- Cicchini, G. M., Anobile, G., & Burr, D. C. (2016). Spontaneous perception of numerosity in humans. *Nature Communications*, 7(1), 12536. <https://doi.org/10.1038/ncomms12536>
- Cohen, Z. Z., Aisenberg, D., & Henik, A. (2018a). The effects of training on tactile enumeration. *Psychological Research*, 82(3), 468–487. <https://doi.org/10.1007/s00426-016-0835-5>
- Cohen, Z. Z., Arend, I., Yuen, K., Naparstek, S., Gliksmann, Y., Veksler, R., & Henik, A. (2018b). Tactile enumeration: A case study of acalculia. *Brain and Cognition*, 127, 60–71. <https://doi.org/10.1016/j.bandc.2018.10.001>
- Cohen, Z. Z., & Henik, A. (2016). Effects of Numerosity Range on Tactile and Visual Enumeration. *Perception*, 45(1–2), 83–98. <https://doi.org/10.1177/0301006615614662>
- Dehaene, S., & Changeux, J. P. (1993). Development of elementary numerical abilities: A neuronal model. *Journal of Cognitive Neuroscience*, 5, 390–407. <https://doi.org/10.1162/jocn.1993.5.4.390>
- de Hevia, M. D., & Spelke, E. S. (2010). Number-Space Mapping in Human Infants. *Psychological Science*, 21(5), 653–660. <https://doi.org/10.1177/0956797610366091>
- DeWind, N. K., Adams, G. K., Platt, M. L., & Brannon, E. M. (2015). Modeling the approximate number system to quantify the contribution of visual stimulus features. *Cognition*, 142, 247–265. <https://doi.org/10.1016/j.cognition.2015.05.016>
- Eger, E., Sterzer, P., Russ, M. O., Giraud, A.-L., & Kleinschmidt, A. (2003). A Supramodal Number Representation in Human Intraparietal Cortex. *Neuron*, 37(4), 719–726. [https://doi.org/10.1016/S0896-6273\(03\)00036-9](https://doi.org/10.1016/S0896-6273(03)00036-9)
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39, 175–191. <https://doi.org/10.3758/BF03193146>
- Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, 8(7), 307–314. <https://doi.org/10.1016/j.tics.2004.05.002>
- Fischer, J., & Whitney, D. (2014). Serial dependence in visual perception. *Nature Neuroscience*, 17(5), 738–743. <https://doi.org/10.1038/nn.3689>
- Fornaciai, M., & Park, J. (2017). Distinct Neural Signatures for Very Small and Very Large Numerosities. *Frontiers in Human Neuroscience*, 11. <https://doi.org/10.3389/fnhum.2017.00021>
- Fornaciai, M., & Park, J. (2018). Serial dependence in numerosity perception. *Journal of Vision*, 18(9), 15. <https://doi.org/10.1167/18.9.15>
- Fornaciai, M., & Park, J. (2020). Neural Dynamics of Serial Dependence in Numerosity Perception. *Journal of Cognitive Neuroscience*, 32(1), 141–154. https://doi.org/10.1162/jocn_a_01474
- Fornaciai, M., & Park, J. (2021). Decoding of EEG Signals Shows No Evidence of a Neural Signature for Subitizing in Sequential Numerosity. *Journal of Cognitive Neuroscience*, 1–15. https://doi.org/10.1162/jocn_a_01734
- Gallace, A., Tan, H. Z., & Spence, C. (2006). Numerosity Judgments for Tactile Stimuli Distributed over the Body Surface. *Perception*, 35(2), 247–266. <https://doi.org/10.1068/p5380>
- Gallace, A., Tan, H. Z., & Spence, C. (2008). Can Tactile Stimuli Be Subitized? An Unresolved Controversy within the Literature on Numerosity Judgments. *Perception*, 37(5), 782–800. <https://doi.org/10.1068/p5767>
- Gallistel, C. R., & Gelman, R. (1991). Subitizing: The preverbal counting process. In F. Craik, W. Kessen, & A. Ortony (Eds.), *Thoughts memories and emotions: Essays in honor of George Mandler* (pp. 65–81). Erlbaum.
- Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, 44, 43–74. [https://doi.org/10.1016/0010-0277\(92\)90050-R](https://doi.org/10.1016/0010-0277(92)90050-R)
- Graham, B., & Lavric, A. (2021). Preparing to switch languages versus preparing to switch tasks: Which is more effective? *Journal of Experimental Psychology: General*. <https://doi.org/10.1037/xge0001027>
- Hochman, S., Cohen, Z. Z., Ben-Shachar, M. S., & Henik, A. (2020). Tactile Enumeration and Embodied Numerosity Among the Deaf. *Cognitive Science*, 44(8). <https://doi.org/10.1111/cogs.12880>
- Hofstetter, S., Cai, Y., Harvey, B. M., & Dumoulin, S. O. (2021). Topographic maps representing haptic numerosity reveals distinct sensory representations in supramodal networks. *Nature Communications*, 12(1), 221. <https://doi.org/10.1038/s41467-020-20567-5>
- Katzin, N., Cohen, Z. Z., & Henik, A. (2019). If it looks, sounds, or feels like subitizing, is it subitizing? A modulated definition of subitizing. *Psychonomic Bulletin & Review*, 26(3), 790–797. <https://doi.org/10.3758/s13423-018-1556-0>
- Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkman, J. (1949). The Discrimination of Visual Number. *The American Journal of Psychology*, 62(4), 498. <https://doi.org/10.2307/1418556>
- Kleiner, M. B., Brainard, D. H., & Pelli, D. G. (2007). What's new in Psychtoolbox-3? *Perception*, 36(2), 301–307. <https://doi.org/10.1068/v070821>
- Knops, A., Piazza, M., Sengupta, R., Eger, E., & Melcher, D. (2014). A Shared, Flexible Neural Map Architecture Reflects Capacity Limits in Both Visual Short-Term Memory and Enumeration. *Journal of Neuroscience*, 34(30), 9857–9866. <https://doi.org/10.1523/JNEUROSCI.2758-13.2014>
- Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review*, 108(2), 393–434. <https://doi.org/10.1037/0033-295X.108.2.393>
- Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology Learning Memory & Cognition*, 26(5), 1124–1140. <https://doi.org/10.1037/0278-7393.26.5.1124>
- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology Learning Memory & Cognition*, 22(6), 1423–1442. <https://doi.org/10.1037/0278-7393.22.6.1423>
- Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, 7(3), 134–140. [https://doi.org/10.1016/S1364-6613\(03\)00028-7](https://doi.org/10.1016/S1364-6613(03)00028-7)
- Monsell, S., & Mizon, G. A. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance*, 32(3), 493–516. <https://doi.org/10.1037/0096-1523.32.3.493>

- Nieder, A. (2012). Supramodal numerosity selectivity of neurons in primate prefrontal and posterior parietal cortices. *Proceedings of the National Academy of Sciences*, *109*(29), 11860–11865. <https://doi.org/10.1073/pnas.1204580109>
- Nieder, A. (2016). The neuronal code for number. *Nature Reviews Neuroscience*, *17*(6), 366–382. <https://doi.org/10.1038/nrn.2016.40>
- Nieder, A. (2017). Magnitude Codes for Cross-Modal Working Memory in the Primate Frontal Association Cortex. *Frontiers in Neuroscience*, *11*. <https://doi.org/10.3389/fnins.2017.00202>
- Nieder, A., & Dehaene, S. (2009). Representation of Number in the Brain. *Annual Review of Neuroscience*, *32*(1), 185–208. <https://doi.org/10.1146/annurev.neuro.051508.135550>
- Piazza, M., De Feo, V., Panzeri, S., & Dehaene, S. (2018). Learning to focus on number. *Cognition*, *181*, 35–45. <https://doi.org/10.1016/j.cognition.2018.07.011>
- Piazza, M., Fumarola, A., Chinello, A., & Melcher, D. (2011). Subitizing reflects visuo-spatial object individuation capacity. *Cognition*, *121*(1), 147–153. <https://doi.org/10.1016/j.cognition.2011.05.007>
- Piazza, M., Mechelli, A., Price, C. J., & Butterworth, B. (2006). Exact and approximate judgements of visual and auditory numerosity: An fMRI study. *Brain Research*, *1106*(1), 177–188. <https://doi.org/10.1016/j.brainres.2006.05.104>
- Pietrini, P., Furey, M. L., Ricciardi, E., Gobbini, M. I., Wu, W.-H. C., Cohen, L., Guazzelli, M., & Haxby, J. V. (2004). Beyond sensory images: Object-based representation in the human ventral pathway. *Proceedings of the National Academy of Sciences*, *101*(15), 5658–5663. <https://doi.org/10.1073/pnas.0400707101>
- Pomè, A., Anobile, G., Cicchini, G. M., Scabia, A., & Burr, D. C. (2019). Higher attentional costs for numerosity estimation at high densities. *Attention, Perception, & Psychophysics*, *81*(8), 2604–2611. <https://doi.org/10.3758/s13414-019-01831-3>
- Revsin, S. K., Piazza, M., Izard, V., Cohen, L., & Dehaene, S. (2008). Does Subitizing Reflect Numerical Estimation? *Psychological Science*, *19*(6), 607–614. <https://doi.org/10.1111/j.1467-9280.2008.02130.x>
- Riggs, K. J., Ferrand, L., Lancelin, D., Fryziel, L., Dumur, G., & Simpson, A. (2006). Subitizing in Tactile Perception. *Psychological Science*, *17*(4), 271–272. <https://doi.org/10.1111/j.1467-9280.2006.01696.x>
- Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology*, *124*(2), 207. <https://doi.org/10.1037/0096-3445.124.2.207>
- Sathian, K., & Zangaladze, A. (2002). Feeling with the mind's eye: Contribution of visual cortex to tactile perception. *Behavioural Brain Research*, *135*(1–2), 127–132. [https://doi.org/10.1016/S0166-4328\(02\)00141-9](https://doi.org/10.1016/S0166-4328(02)00141-9)
- Sengupta, R., Bapiraju, S., & Melcher, D. (2017). Big and small numbers: Empirical support for a single, flexible mechanism for numerosity perception. *Attention, Perception, & Psychophysics*, *79*(1), 253–266. <https://doi.org/10.3758/s13414-016-1221-5>
- Tian, Y., & Chen, L. (2018). Cross-modal attention modulates tactile subitizing but not tactile numerosity estimation. *Attention, Perception, & Psychophysics*, *80*(5), 1229–1239. <https://doi.org/10.3758/s13414-018-1507-x>
- Togoli, I., & Arrighi, R. (2021). Evidence for an A-Modal Number Sense: Numerosity Adaptation Generalizes Across Visual, Auditory, and Tactile Stimuli. *Frontiers in Human Neuroscience*, *15*, 713565. <https://doi.org/10.3389/fnhum.2021.713565>
- Togoli, I., Marlair, C., Collignon, O., Arrighi, R., & Crollen, V. (2021). Tactile numerosity is coded in external space. *Cortex*, *134*, 43–51. <https://doi.org/10.1016/j.cortex.2020.10.008>
- Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review*, *101*(1), 80–102. <https://doi.org/10.1037/0033-295X.101.1.80>
- Vetter, P., Butterworth, B., & Bahrami, B. (2008). Modulating Attentional Load Affects Numerosity Estimation: Evidence against a Pre-Attentive Subitizing Mechanism. *PLoS ONE*, *3*(9), e3269. <https://doi.org/10.1371/journal.pone.0003269>
- Whalen, J., Gallistel, C. R., & Gelman, R. (1999). Nonverbal Counting in Humans: The Psychophysics of Number Representation. *Psychological Science*, *10*(2), 130–137. <https://doi.org/10.1111/1467-9280.00120>
- Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*(1), B1–B11. [https://doi.org/10.1016/S0010-0277\(99\)00066-9](https://doi.org/10.1016/S0010-0277(99)00066-9)
- Xu, F., Spelke, E. S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science*, *8*(1), 88–101. <https://doi.org/10.1111/j.1467-7687.2005.00395.x>
- Xu, Y. (2009). Distinctive Neural Mechanisms Supporting Visual Object Individuation and Identification. *Journal of Cognitive Neuroscience*, *21*(3), 511–518. <https://doi.org/10.1162/jocn.2008.21024>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.