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Asymmetric switch cost between subitizing and estimation in tactile modality

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Abstract

Subitizing (enumerating four or fewer objects) and estimation (enumerating ve 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 e ect). 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 ndings 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 signi cance 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), re ecting 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 speci c 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

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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; Pome 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 consecutive numbers generates a larger proportion of change in a subitizing range (e.g., 100 % increase from 1 to 2) than in an estimation range (10 % increase from 10 to 11) (Gallistel & Gelman, 1991, 1992). In this way, identification of number differences in subitizing range is less difficult and more precise. Recently, some human brain imaging studies (Cai et al., 2021; Fornaciai & Park, 2017, 2021) provided new evidence for "single estimation component hypothesis". For example, a study used sequentially presented numerosity by electroencephalogram signals decoding technique and found there was no sharp representational difference between items across the subitizing boundary. In this case, they suggested that there was only one single perceptual mechanism encoding sequential numerosities (Fornaciai & Park, 2021).

"Single object-individuation component" hypothesis presumes that subitizing is based on a capacity-limited, domain-general mechanism, known as object individuation (OI). At OI stage, people divide items based on their spatial/temporal details, that is, individualization (Xu, 2009). In this vein, the limited capacity of individualized items in subitizing is contingent on OI's limited resources (Trick & Pylyshyn, 1994; Xu, 2009). Estimation, on the other hand, is based on ANS. Revkin et al. (2008) asked participants to name the numerosity of displays taken from two sets matched on discrimination difficulty (1,2,3,4,5,6,7,8 and 10,20,30,40,50,60,70,80). The results showed that after eliminating the interference of discrimination difficulty, participants still had higher precision in small numerosity range (1-4) compared to large numerosity range (10-40). Thus, they refuted the "single estimation component hypothesis" and supported that there was a mechanism dedicated specifically to apprehending small numerosities less than 4. And some researchers found that the subitizing capacity could be weakened by ongoing tasks based on object individuation mechanism, such as, visual working memory tasks (Piazza et al., 2011) and multi-object tracing task (Chesney & Haladjian, 2011). Therefore, they believed that OI was the mechanism dedicated specifically to subitizing.

The recently proposed "dual component hypothesis" emphasizes on how attentional resources is employed in enumeration. ANS operates on both small and large numerosities range, irrespective of the availability of attentional resources. Unlike ANS, OI relies heavily on attentional resources (Anobile et al., 2012, 2016). When attentional resources are available, OI as an additional mechanism sit on top of ANS, supports rather than replaces estimation (Anobile et al., 2016a, b). And the role of ANS is shielded by OI, showing higher accuracy and precision (Burr et al., 2010). However, when attentional resources are deficient, ANS (with a low dependency on attentional resources) prevails over OI in small number enumeration (Cheng et al., 2021), resulting in a decrease in accuracy and precision. This relatively high dependency on attentional resources in subitizing has been supported by dual task experiments (Burr et al., 2010; Tian & Chen, 2018). For example, in a dual task consisted of enumeration and working memory, enumerations for small numerosity range were deteriorated in high load conditions, while the performance remained intact on a larger numerosity range no matter whether the attentional load was high or low (Burr et al., 2010). Unlike the "single estimation component hypothesis" which believes that subitizing and estimation originate from the same process, the "single object-individuation component hypothesis" and "dual component hypothesis" assume that subitizing is distinct from estimation. However, the "single

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 nger. 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 dif erent).

According to the previous studies, they used a paradigm where participants were rst 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 ef ect, identi ed 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 in uential explanations is task-set recon guration

Experiment 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 (η^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 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 1kHz, 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.

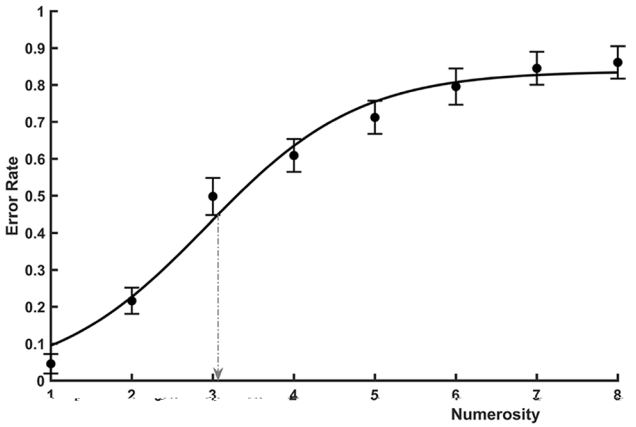

Fig. 1 The error rate result of Experiment 1. The curve showed the fitted sigmoid functions for average data. Arrows indicate tactile subitizing capacities measured from the inflection point of the fitting functions.

Results and Discussion

We compared the error rate (ERR) of participants responses with a repeated-measured analysis of variances (ANOVA[1]) and found a significant main effect of numerical range ($F_{(3.034,\ 60.861)}$ =134.12, p<.001, η^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

Experiment 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 ect) and the numerical range of S1 numerical range of S2 ISIs interaction (preparation ect). Thus, we took the ect size of the switch cost ect (η^2_p=.497) and the preparation ect (η^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 ect sizes of switch cost ect and preparation ect 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 llers, which made up 25% of total trials. Here, under the no-switch condition the numerical ranges of the rst 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 dered 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 rst array of stimuli from the second one. To investigate the possible preparation ect, 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 rst tactile pins array (derent 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 xation 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 in uence of working memory on derent 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 xation duration: 500 -1000 ms). There were 320 trials in each sub-experiment, 80 of which were llers. 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 ect, 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

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

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

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

CoV and WF were rst 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) 2 (numerical range of S2: subitizing vs estimation) 4 (ISI:100 ms, 250 ms, 400 ms, and 550 ms) repeated-measured ANOVA test on ERR of reporting S2. There was a signi cant three-way interaction on ERR ($F_{(2.262, 56.553)}$ =10.19, p<.001, η^2_p =.29). Simple e ect analysis revealed that signi cant two-way interaction ($F_{(1, 25)}$ =16.65, p<.001, η^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, η^2_p =.50). Correspondingly, the ERR of the S-E condition (*M* =.78, *SE*

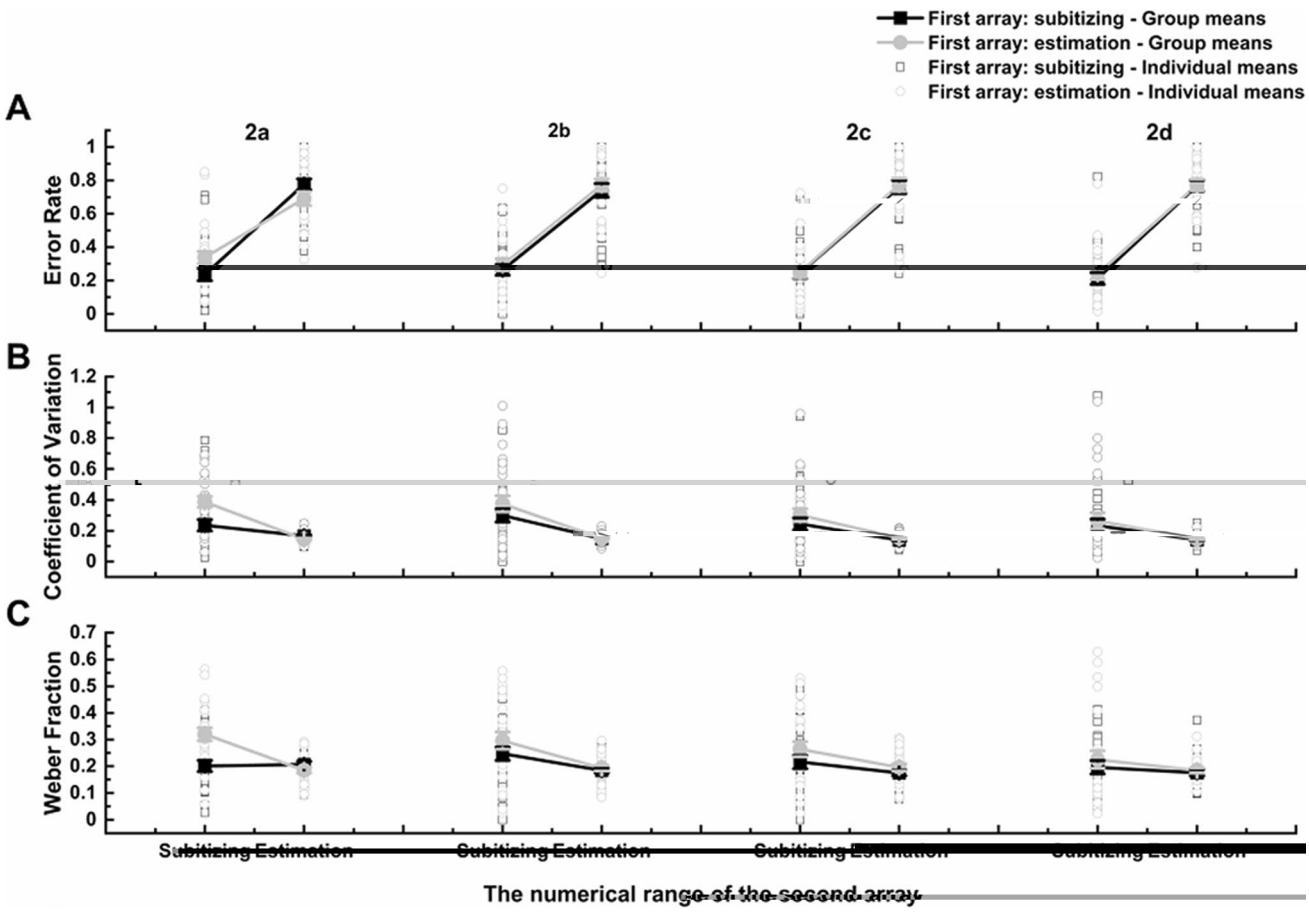

Fig. 3 Results of Experiment 2. These three panels showed the group and individual means of the participants performance on the second enumeration task, including Error Rate (**A**), Coefficient of variation (**B**) and Weber Fraction (**C**). From left to right in each panel were the results of Experiment 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) 2 (numerical range of S2) 4 (ISI) on CoV displayed a significant three-way interaction ($F_{(3, 75)}$ =4.01, p=.011, η^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, η^2_p =.48) and 2b ($F_{(1, 25)}$ =5.73, p=.025, η^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, η^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, η^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, η^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:

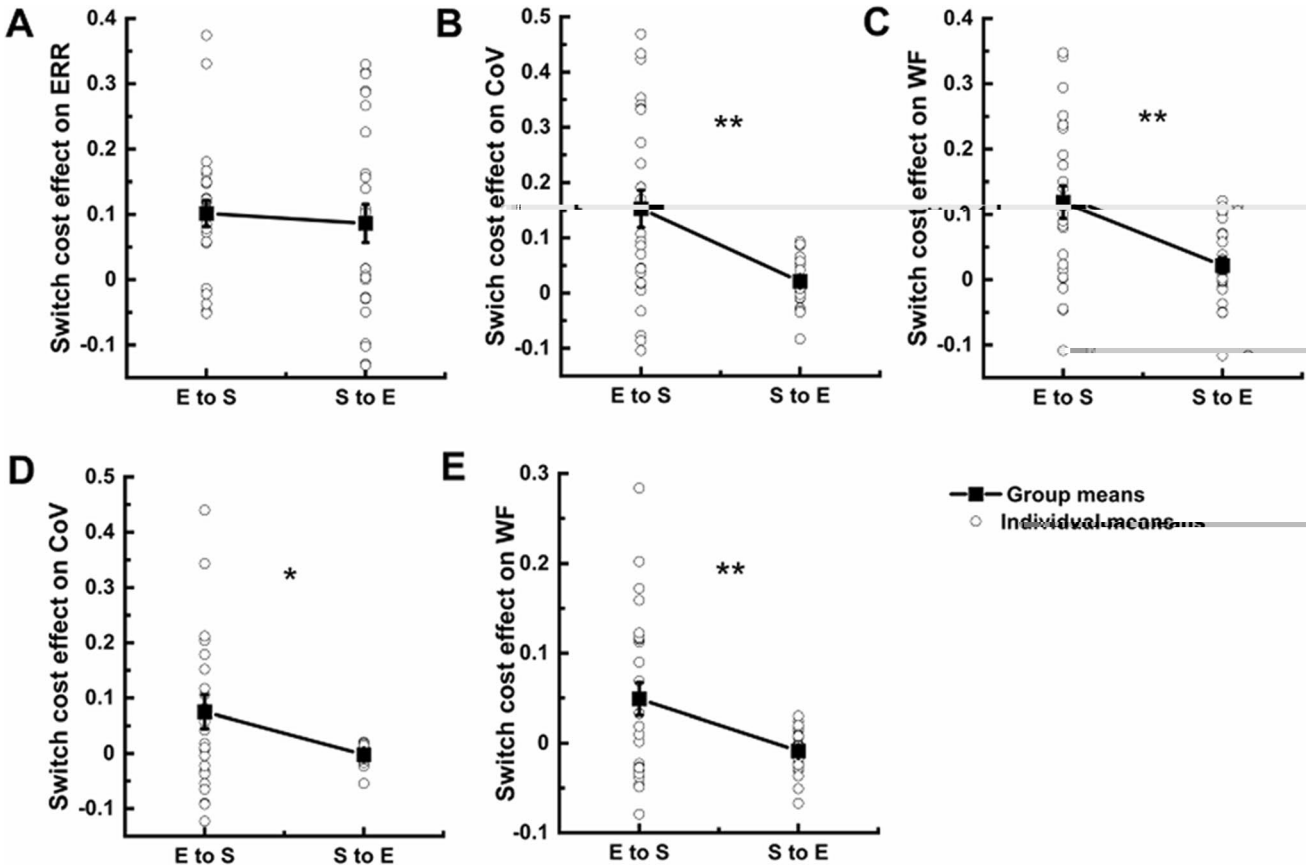

Fig. 4 The switch cost effect of Experiment 2a and Experiment 2b. The switch cost effects were defined as the differences between the switch condition and the no-switch condition on Error Rate (**A**), Coefficient of variation (**B**), and Weber Fraction (**C**) of Experiment 2a, and on Coefficient of 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 date 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) 2 (numerical range of S2) 4 (ISI) applied on CoV displayed a significant main effect of S1 range ($F_{(1, 25)}$ =20.94, p<.001, η^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, η^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, η^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) 2 (numerical range of S2) 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 signi cant three-way interaction ($F_{(3, 75)}$ =4.96, p=.003, η^2_p =.17; see Fig. 3C). Simple analysis showed that the two-way interactions between the numerical range of S1 and S2 were both signi cant in Experiment 2a ($F_{(1, 25)}$ =22.81, p<.001, η^2_p =.48) and 2b ($F_{(1, 25)}$ =4.78, p=.038, η^2_p =.14). Further analysis showed that in Experiment 2a when the numerical range of S2 was within subitizing, a signi cant precision reduction ($F_{(1, 25)}$ =23.01, p<.001, η^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 signi cant dif erence ($F_{(1, 25)}$ =3.49, p=.074, η^2_p =.20) between the S-E and the E-E conditions. We found the same results in Experiment 2b. Speci cally, when the numerical range of S2 was within subitizing, a signi cant precision reduction ($F_{(1, 25)}$ =7.27, p=.012, η^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 signi cant dif erence 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 ($WF_{sub\text{-}est}$ $WF_{est\text{-}est}$, Exp. 2a: M =.12, SE =.02; Exp. 2b: M =.05, SE =.02) generated a larger cost than the switch in the opposite direction ($WF_{est\text{-}sub}$ $WF_{sub\text{-}sub}$, 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) 2 (numerical range of S2) 4 (ISI) applied on WF also displayed a signi cant main ef ect of S1 range ($F_{(1, 25)}$ =24.81, p<.001, η^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 ef ect of the S2 range was also signi cant ($F_{(1, 25)}$ =14.211, p=.001, η^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 ef ect of ISI was signi cant ($F_{(3, 75)}$ =4.40, p=.007, η^2_p =.15), indicating an improvement in the precision with the increase of ISI. Post hoc analysis showed that there was signi cant dif erence (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 signi cant switch ef ects on all dependent variables, when ISI was 100 ms. Importantly, the switch ef ects were asymmetric on CoV and WF. However, there was no signi cant 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 recon guration could explain the absence of switch cost, that participants obtained suf cient 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 rst array (P1), (b) the mere exposure to the second array (P2), and (c) the potential extra cost of the numerical processing from the rst array to the second array that was speci cally based on the numerical relationship of their numerosity ranges (denoted as N1▲N2, a switch or

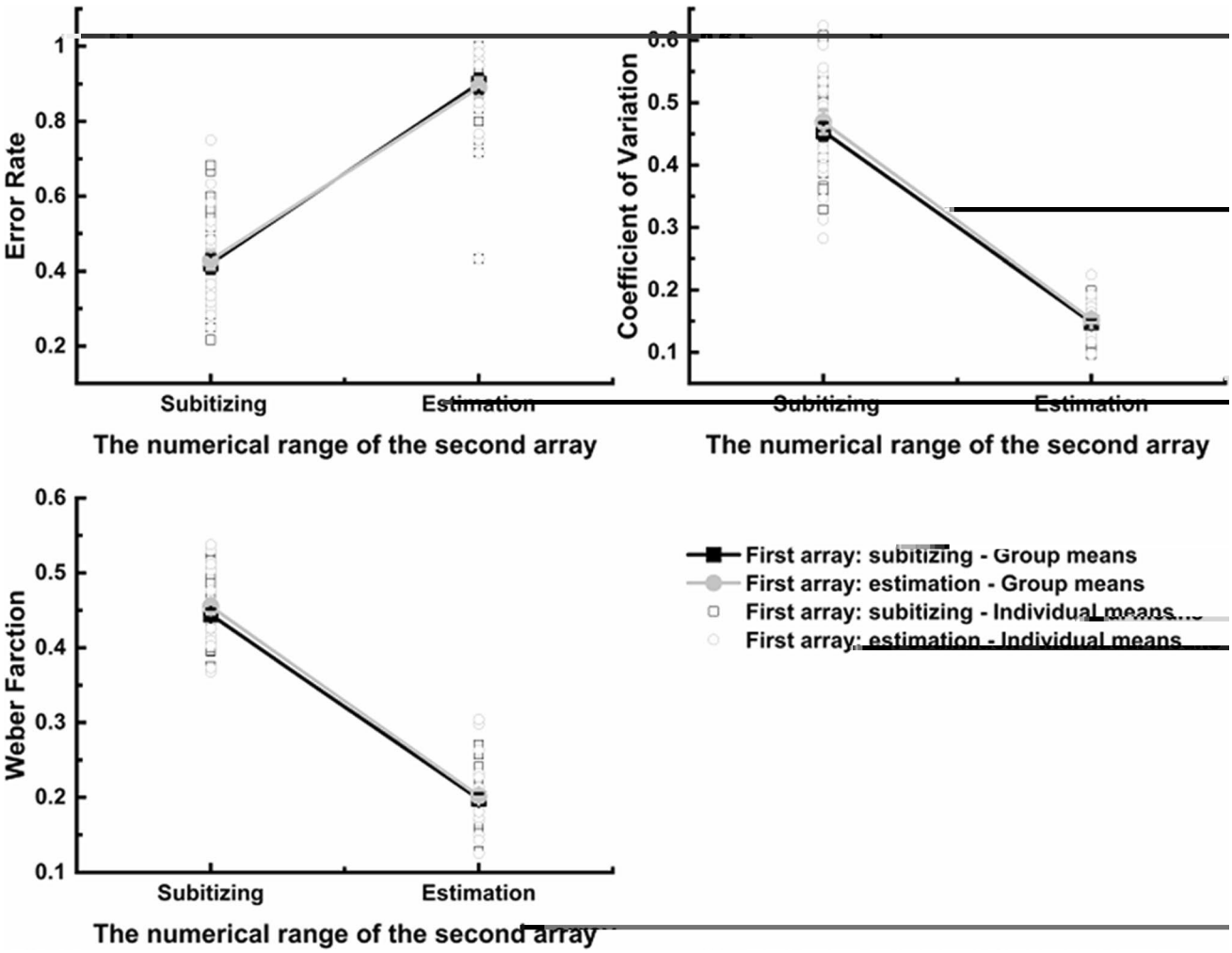

Fig. 5 The results of Experiment 3. The gure showed the group and individual means of the participants performance on single task 2 including the Error Rate (**A**), Co cient of variation (**B**), and Weber Fraction (**C**). Other aspects of the gure format were similar to Fig. 3.

no switch across subitizing and estimation processes). The E2 received in uences from all above 3 factors (E2 = P1 + P2 + N1▲N2). However, the performance of the single task 2 in Experiment 3 (denoted here as E3), in which the rst array should be ignored without further numerical processing, received in uences from only 2 factors (E3 = P1 + P2). In this case, we believed that if there was no switch cost e ect 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 e ect of the S2 range was signi cant on all dependent variables (ERR: $F_{(1, 25)}$ =321.31, p<.001, η^2_p =.93; CoV: $F_{(1, 25)}$ =356.84, p<.001, η^2_p =.94; WF: $F_{(1, 25)}$ =557.94, p<.001, η^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 rst array could also capture some attentional resources and in uenced the precision of task 2. Importantly, the results revealed no signi cant 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 con rmed that di erences 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) 2 (numerical range of S2) 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 signi cant three-way interaction on ERR ($F_{(1, 50)} = 12.42$, $p = .001$, $\eta^2_p = .20$), CoV ($F_{(1, 50)} = 19.08$, $p < .001$, η^2_p

(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 dr erent 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 rst numerical processing signi cantly in uenced the second numerical processing when ISI between the two events was 100 ms. Speci cally, 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 e ect. The relationship between subitizing and estimation in tactile modality accorded closely with the "dual component c(h 4(t and lar)15.8(g)14.6999 po9.299999237(icTJ-.001 Tc0 -1sis (-)T,)37( )izin7()1.6(apaalTc-.0(t)-8.3Tc.08 Tw702999996948(be)is

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