Acta Psychologica 150 (2014) 26–34

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Tactile enumeration of small quantities using one hand

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ARTICLE INFO

Article history:
Received 7 June 2013
Received in revised form 25 March 2014
Accepted 28 March 2014
Available online 8 May 2014

PsycINFO classification:
2300
2340

Keywords:
Tactile subitizing
Finger counting
Embodied numerosity
Tactile stimuli

ABSTRACT

Our study explores various aspects of enumerating small quantities in the tactile modality. Fingertips of one hand were stimulated by a vibro-tactile apparatus (for 100/800 ms). Between 1 and 5 stimuli were presented to the right or the left hand and applied to neighboring (e.g., thumb–index–middle) or non-neighboring (e.g., thumb–middle–pinkie) fingers. The results showed a moderate increase in RT up to 4 stimuli and then a decrease for 5 stimuli. Right hand stimulation evoked more accurate performance than left hand stimulation only under short exposures (100 ms). Importantly, when the stimuli were presented to neighboring fingers, the accuracy rate was higher and the RT was faster than when presented to non-neighboring fingers. We discuss the results and suggest that when the stimuli are presented to one hand the subitizing range is 4 rather than 3. Furthermore, the right hand advantage and the efficiency for neighboring fingers are further support for the association between number and spatial arrangement of the fingers.

1. Introduction

1.1. Embodied numerosity

The body plays a central role in modulating the mind. This viewpoint is known in cognitive science as embodied cognition. It holds that cognitive processes are deeply rooted in the body's interactions with the environment. Hence, human cognition, rather than being abstract, may have been grounded in previous sensorimotor experience of the body (Wilson, 2002). This view has received support from both behavioral and neuroscientific investigations (e.g., Barsalou, 2008; Fischer & Zwaan, 2008).

The use of body parts, most often the fingers, is a common technique used in counting (Previtali, Rinaldi, & Girelli, 2011). It has been suggested that the fingers may be instrumental to the development of numerical cognition (Andres, Di Luca & Pesenti, 2008), and that the use of fingers is the origin of the base-10 Hindu-Arabic numeral system (0–9 digits). Moreover, brain imaging studies showed that the finger schema involves the same neuroanatomical regions (i.e., parietal network) as the processing of numbers (Pesenti, Thioux, Seron, & De Volder, 2000; Piazza, Mechelli, Butterworth, & Price, 2002; Pinel, Piazza, Le Bihan, & Dehaene, 2004). Fischer and Brugger (2011) suggested that the association between number and space (through fingers) reflects the human capacity to quickly learn to associate any symbol or abstract relation with a spatial position or spatial relationship, and these associations are "the expression of some general cognitive rule that reflects the 'placement' of an image in space (the spatialization of ideas)" (p. 5). Domahs, Moeller, Huber, Willmes, and Nuerk (2010) referred to the fingers' influence on the structure of abstract mental number representations as "embodied numerosity". Domahs, Krinzinger, and Willmes (2008) suggested that the base-10 Hindu-Arabic numeral system is structured by "the gap between both hands". Namely, when we mentally calculate, we are operating with a representation of two sets of five fingers, thus forming "chunks" of five (i.e., sub-base-five). This sub-base-five effect has been shown in children and adults (Domahs et al., 2010). This was also found to affect responses in other tasks involving numerical judgments (Cohen Kadosh, 2008; Naparstek & Henik, 2012; Tzelgov, Meyer, & Henik, 1992). Thus it was suggested that finger counting *shapes* numerical mental representations. However, it is important to note that there is new growing literature suggesting that finger counting is not *a necessary* tool for the development of numerical representations, and that the fingers do not necessarily play a central role in modulating numerical cognition (for examples see Krause, Bekkering, & Lindemann, 2013; Plaisier & Smeets, 2011b; Thevenot et al., 2014).

Finger counting enables the creation of a stable order principle due to the habit of linking specific fingers to specific objects in a sequential, culture-specific order (Fayol & Seron, 2005; Wiese, 2003a,b). However, the question about which hand to start counting with varies between research studies. Lindemann, Alipour, and Fischer (2011) reported

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http://dx.doi.org/10.1016/j.actpsy.2014.03.011
0001-6918/

that while most Western individuals started counting with the left hand and associated the number 1 with their thumb, most Middle-Eastern respondents preferred to start counting with the right hand and preferred to map the number 1 onto their little finger (i.e., pinkie). They also noted that the preference for the hand to start with varied strongly between individuals and was independent of handedness. These findings seem to be affected by reading habits as well. Specifically, Shaki, Göbel, and Fischer (2010) demonstrated that Israeli children initially start counting on their left side but when they learn to read and write Hebrew (a language written from right to left) they prefer starting on their right side. Sato, Cattaneo, Rizzolatti, and Gallese (2007) demonstrated a close relationship between hand/finger and numerical representations. They asked participants to perform parity judgments on small (1 − 4) and large (6 − 9) numbers while inducing TMS (transcranial magnetic stimulation) to the right or left hand muscle. Their results suggested overlapping representations for small numbers (1–4) and fingers of the right hand, with no modulation for the left hand. Thus, it seems that finger counting habits may vary substantially both within and between cultures, with individual differences within the same population that can be explained by taking handedness into consideration (Previtali & Girelli, 2009; Previtali et al., 2011; Sato & Lalain, 2008).

1.2. Enumeration: subitizing and counting

Research on enumeration distinguishes between counting and subitizing. The latter refers to reporting the number of presented items in a small group (up to about four items), and is considered an automatic, effortless process. Counting (five items and up), in contrast, involves attention and is an effortful, serial process (Kaufman, Lord, Reese, & Volkmann, 1949). Generally, response time (RT) increases and accuracy decreases as the number of visually presented items increases. However, this increase does not create a continuous slope: when the number of items is in the subitizing range, the slope is shallow, with much more accurate and confident responses. In contrast, from five items and above, a much steeper slope is observed, with decrease in confidence and accuracy (Kaufman et al., 1949; Trick & Pylyshyn, 1994). This discontinuity indicates the change from subitizing to the counting process.

Enumeration has been studied mostly with visual presentations. Namely, participants are presented with a display of dots, and asked to report the number of dots they see. Recently, subitizing has also been observed in other modalities including the tactile modality; participants were asked to report the number of stimuli they felt on their body. For the tactile or haptic input surface, some of the studies use actively touching palms of hand and fingers (i.e., active touch — touching with finger exploration; Plaisier, Bergmann Tiest, & Kappers, 2009), or passively stimulating fingertips (i.e., passive touch — enumerating the number of stimuli presented to the fingertips, without finger movements; Riggs et al., 2006). It was found that tactile subitizing is not similar to visual subitizing, and unlike the robust findings with visual subitizing, the findings regarding tactile subitizing are sparse and inconclusive (see Gallace, Tan, and Spence (2008) for the controversy regarding the existence of tactile subitizing); First, RT slopes for tactile subitizing are generally steeper than those for the visual modality (tactile modality: 260 ms/item — Riggs et al., 2006, and 130 ms/item — Plaisier & Smeets, 2011a; visual modality: 40–100 ms/item — Akin & Chase, 1978; Mandler & Shebo, 1982; Simon, Peterson, Patel, & Sathian, 1998; Trick & Pylyshyn, 1993). Second, there is a difference in the function relating RT and number of items. In the visual modality, RT increases as the number of items increases. In the tactile modality, when the fingers were the input surface, RT was shown to increase for up to five or six items and then decrease. Furthermore, it was suggested that the subitizing range was three rather than four (Plaisier & Smeets, 2011a; Riggs et al., 2006). This was found for both active touch and passive touch.

Importantly, studies reporting the existence or lack of tactile subitizing differ greatly in the methods applied. This led Gallace et al. (2008) to point out several issues to be considered when studying tactile enumeration. 1) Duration of stimuli presentation — the fingers were exposed to the stimuli for 100 ms in Gallace et al.'s study, and until response in Riggs et al.'s (2006) study. Gallace et al. suggested that because subitizing is a pre-attentive process (e.g., Kaufman et al., 1949; Peterson & Simon, 2000; Trick & Pylyshyn, 1993, 1994), it can only be studied under short durations of stimuli presentations. 2) Distribution of stimuli across the skin surface — Gallace and colleagues suggested that "lack of subitizing in tactile perception might be related to inhibitory interactions of inputs from simultaneous or near-simultaneous tactile inputs across the skin surface" (p. 791). Our body surface has a primary somatotopical organization in the parietal cortex. The secondary and bilateral representation in other brain areas interacts with our primary somatosensory cortex, yielding interhemispheric interactions between homologous skin regions (Braun, Hess, Burkhardt, Wühle, & Preissl, 2005). Thus, the lack of subitizing might be related to errors made due to the distribution of stimuli across neighboring fingers and similar fingers of both hands (see also Harris, Harris, & Diamond, 2001). 3) Mean RT slopes — when tactile RT slopes (in Riggs et al.'s study) are much steeper than the RT slopes for visual subitizing, it implies that counting rather than subitizing was performed.

2. The current study

The aim of the current study was to examine various aspects of enumerating tactile stimuli using one hand among adults. To the best of our knowledge, no previous study has examined passive tactile enumeration while applying stimuli to all five fingers of one hand only and compared responses between hands. Specifically, we wanted to address the following questions: 1) Will tactile subitizing (i.e., up to three fingers) appear when applying stimulation to all five fingers on one hand? 2) Will this differ as a function of hand or exposure time? 3) Will distribution of stimulation modulate performance?

We carried out two experiments asking right-handed participants to vocally report, as fast and accurately as possible, the number of fingers stimulated. In each trial between one and five fingers (thumb, index, middle, ring and pinkie) of one hand were stimulated simultaneously. Stimuli were presented to the right and left hand (dominant and the non-dominant hand, respectively), in separate blocks. We applied stimuli to all five fingers, including the thumbs since the thumbs have an essential role in finger counting and because of their relatively high sensitivity (Johansson & Vallbo, 1979).

2.1. Subitizing

Participants were tested on each hand separately in order to focus on the tactile subitizing range (up to three fingers) and to eliminate interference of stimulation from the other hand (Braun et al., 2005; Gallace et al., 2008). The difference between subitizing and counting was determined by analyzing the difference in the slope values of small numerosities (1–3) and medium numerosities (3–4). We used trend analysis and compared the slopes of accuracy rates and RT means. Also, we explored the mean and frequency of numerical responses made by participants.

2.2. Hand differences

Studies of active touch enumeration (Plaisier, Bergmann Tiest, & Kappers, 2010a) and sensory tasks (such as finger localization, or tasks where performance is highly dependent on fine spatial acuity like Braille reading and pattern recognition) showed no remarkable difference between hands (Finlayson & Reitan, 1976; Kaplan-Solms & Saling, 1988; Van Boven, Hamilton, Kauffman, Keenan, & Pascual-Leone, 2000; Vega-Bermudez, Johnson, & Hsiao, 1991) in spite of better motor performance with the dominant hand. However, factors like handedness, starting-hand counting preference, and reading–writing