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Distinct mechanisms in the numerosity processing of random and regular dots

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ABSTRACT

This study investigated the mechanisms of the numerosity coding of random and regular dot distribution patterns. Experiment 1 revealed that connectedness significantly affected the numerosity perception of randomly distributed dots, and two adjacent dots were considered to be one numeral unit when connected via lines. The connectedness effect was much weaker on the numerosity perception of regularly distributed dots in vertical or horizontal queues and was absent in the perception of dots in diagonal queues. Experiment 2 demonstrated that randomly distributed adaptors induced a stronger effect of adaptation compared with regular adaptors when random dots after adaptation were used to test participants' numerosity perception. Experiment 3 found that the change in stimulus orientation has no effect on adaptation for random patterns. However, for regular patterns, adapting stimuli with an orientation identical to the tests caused stronger aftereffects compared with those with a different orientation. In Experiment 4, when random adaptors were presented in one eye of a participant, the adaptation aftereffect was shown to exist in both the exposed and un-exposed eyes (binocular transfer), whereas the aftereffect of regular adaptors remained only in the exposed eye (monocular transfer). We interpret that distinct mechanisms might control the numerosity processing of randomly and regularly distributed dots. Generic numerosity processing seems to be automatically inhibited based on the coding of regular patterns. The absence of numeral unit individuation, which is coded at a higher visual-processing level, might play an important role in this inhibition.

1. Introduction

Both humans and nonhumans are capable of numerosity cognition (Dehaene, 1992, 2002; Feigenson, 2011; Kramer, Bono, & Zorzi, 2011). As a sense that emerges from the processing of surrogate texture features (Franconeri, Bemis, & Alvarez, 2009), numerosity processing should be independent of other visual feature processing. Previous studies have confirmed the independence of numerosity processing with regard to the processes associated with stimuli size, shape, orientation, contrast, and configuration (Burr & Ross, 2008a, 2008b; Liu, Zhang, & Zhao, 2012; Liu, Zhang, Zhao, Liu, & Li, 2013). However, there remains a question concerning the relationship between numerosity and density processing. This question is unavoidable because its answer determines the quality of numerosity processing: is it an independent mechanism or merely a by-product of texture density processing?

A series of studies demonstrate the distinguishing characteristics of numerosity processing. The Hierarchical Generative Model (Stoianov & Zorzi, 2012) suggests that number sense gradually ignores texture features and emerges as a statistical feature from texture across the activities of three hierarchical processing levels (Stoianov & Zorzi, 2012). Burr and Ross (2008a) propose that numerosity adaptation is evidence of an independent numerosity processing mechanism. Numerosity adaptation refers to the effect of adaptor numerosity on observer quantity perception. Participants were asked to gaze at the centre of a screen while adaptors were displayed (400 dots in one hemifield and 10 dots in the other). Significant changes in perceived numerosity were found when participants compared dot numerosity after adaptation. When 100 dots were displayed in the hemifield where the 400-dot adaptor had been, participants reported that the stimuli were as numerous as 30 dots displayed in the other hemifield (Burr, 2013; Burr & Ross, 2008a; Butterworth, 2008; Durgin, 1995; Ross & Burr, 2010). However, researchers have argued that density adaptation plays an important role in the Burr and Ross adaptation because numerosity is highly related to density (Durgin, 2008). Anobile, Cicchini, and Burr (2014) note that numerosity and density are not always distinguishable. With moderate

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density, the changing mode of the Weber fraction stayed constant (i.e., thresholds increased directly with numerosity) regardless of whether participants compared the numerosity or the density of stimuli pairs. When the dots became denser, however, a new changing mode appeared with regard to the sensitivity of discrimination (i.e., the thresholds increased with the square root of texture density). This finding suggests that denser dots inhibit numerosity processing; thus, density cognition supersedes this processing (Anobile et al., 2014). That study proposes that the individuation of a numeral unit (i.e., a single dot) is critical to the processing of numerosity. As the dots became denser, it became more difficult to separate individuals as numeral units from the crowding texture (Anobile, Turi, Cicchini, & Burr, 2015; Anobile et al., 2014). Therefore, numerosity processing was inhibited when dots became too crowded to separate as individual units.

Individuation and the presentation of numeral units likely play important roles in numerosity processing. Two different stages might control the coding of numerosity: the individuation of items in a visual display and, subsequently, the magnitude estimation based on the distinct number of items (Gallistel & Gelman, 2000). Studies have demonstrated the existence of individuation in numerosity processing. For example, when randomly distributed dots were connected via lines, the perceived magnitude was significantly reduced. Thus, two dots connected via a line were often considered to be one when observers compared the number of dots, some of which were connected in pairs (Franconeri et al., 2009; He, Zhang, Zhou, & Chen, 2009; Milne et al., 2013). Studies have suggested that grouping has an effect on early individuation mechanisms, which in turn might be important for numerosity estimation (Mazza & Caramazza, 2012). In fact, Liu et al. found that when separate adaptor dots were perceptually grouped into chunks (i.e., the grouping was induced via colours or dot distribution regulations), observers adapted to the number of chunks rather than the number of dots. This result suggests that both numerosity perception and adaptation are based on the number of units after individuation. Individuation is not only important but also necessary in numerosity cognition. Without proper numerical units, the results of numerosity processing might be meaningless. The inhibition of individuation might be synchronic with the inhibition of generic numerosity processing (Liu et al., 2013).

According to the above-described studies, increasing difficulty in separating individuals as numerosity units should be responsible for the inhibition of generic numerosity processing when denser dots are coded. If this is the case, then a crowding-like effect might not be the only way to inhibit numerosity processing. Other texture properties that could cause difficulty in individuation should also cause inhibition of numerosity processing. For example, it is likely to be difficult to separate single dots as numeral units when they are distributed with high regularity because the overall configuration (which always "pops out" from regular distributions) emphasises meaningful information, and observers are likely to understand the pattern by analysing the spatial relationships between one dot and its fellows in another "neighbourhood" instead of by separating a single dot and analysing it without context. This study hypothesised that regularly distributed dots (e.g., well-proportioned distributed dots or dots distributed in queues) inhibit generic numerosity processing. Increasing difficulty in numeral unit individuation should contribute to numerosity processing inhibition when regular patterns are coded.

Numerosity processing is proposed to be composed of several steps that involve distinct levels. Distinct mechanisms are proposed with regard to numerosity processing both with and without awareness. Conscious numerosity processing is based on the function of high-level processes such as object individuation. Because awareness is necessary in high-level processing (Sweeny, Grabowecky, & Suzuki, 2011), numeral units' individuation and representation are inhibited in numerosity processing when awareness is absent (Liu et al., 2013). Both low- and high-level processing are found to be engaged in parallel to accomplish conscious numerosity cognition, whereas when individuation is inhibited, only the primary low-level steps are involved in unconscious numerosity processing (Liu et al., 2013; Zhang, Liu, Zhao, Zhang, & Wu, 2014). Inhibition of individuation plays an important role in the absence of high-level numeral processing. In this study, we investigated the influence of regular dot distribution on numerosity processing and examined the level of the visual system at which that influence occurs. Given that regular patterns affected numerosity processing via individuation inhibition, inhibition should primarily be revealed at higher levels—not primary levels—of numerosity processing.

A reduction in the connectedness effect indicates the inhibition of individuation. Experiment 1 compared the effect of connectedness on numerosity estimation in random and regular dots. Our hypothesis suggested that the reduction or even absence of individuation associated with numeral units might be expected with regard to the coding of regularly distributed dots. A dramatic decrease in quantity perception related to the number of lines that connect the dots should disappear. Connecting dots with lines should have a different or even no influence on numerosity perception in regular patterns than in random patterns.

Based on Experiment 1, because observers might adopt strategies for experimental tasks, it would be unconvincing to propose that inhibition is the only reason for the possible change in the connectedness effect of regular patterns. Therefore, in Experiment 2, we investigated the effect of dot distribution on numerosity adaptation. If regularly distributed dots inhibited individuation (or in other words, it inhibited several steps in numerosity processing), then a decrease in the adaptation aftereffect induced by adaptors with regular dots should be expected compared to adaptors with random dots when numerosity perception is measured using random dots. Here, the adapting paradigm was adopted to examine the existence of automatic processing. Because adaptation occurs prior to the testing stage, any change in the adaptation effect should be attributed to the automatic coding of the adaptors, which is not task relevant. A greater adaptation effect should indicate additional processing. Therefore, the reduction in adaptation to regular adaptors indicates the automatic inhibition of numerosity processing when regular patterns are coded.

Questions remain following Experiment 2. If inhibition is revealed by a reduction in adaptation effects induced by regular patterns, it can be attributed to several factors, such as the average dot distance, the proximity between the adapting and testing patterns, or the entrance into play of specific spatial frequency channels. Spatial frequency and other texture-based features are mainly coded in primary visual areas (Sweeny et al., 2011). These potential factors might affect low-level numerosity processing. If regularity is proved to inhibit higher levels of numeral processing, then individuation inhibition will be emphasised in explaining the effects revealed in Experiments 1 and 2. Two additional experiments were therefore included to collect more evidence that regularity inhibits higher levels of numeral processing. Experiments 3 and 4, which compared the processing levels of numerosity adaptation induced by random and regular patterns, both helped to rule out more "texture-based" explanations for the inhibition and to more strongly support an explanation based on individuation inhibition.

As visual information is processed from primary to higher levels along the ventral pathway, presentation of the information should transfer from a specific to an abstract format (Dehaene & Changeux, 1993), and the neuron bases involved should range from simple to complex (Harris, Schwarzkopf, Chen, Bahrami, & Rees, 2011; Sweeny et al., 2011). Inversely, the processing levels of a visual property can be inferred by analysing the elements' specificity and the interocular transfer of its coding aftereffects (Burr & Ross, 2008a; Durgin, 2001). Numerosity processing was relatively texture-element non-specific, and its adaptation was independent of the dots' orientation (Burr & Ross, 2008a). The Number Detector Model (Dehaene & Changeux, 1993) proposed that when numerical units were represented, activation that synchronised with stimulus size or other specific features should be "normalised" so that the processing could lead to an abstracted representation of a number. In Experiment 3, we proposed that numerosity adaptation in