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Subitizing as pattern recognition: evidence for automaticity when non-symbolic number stimuli are canonically arranged

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Subitizing allows detecting the quantity of a small set of elements (up to four) with the accuracy of counting and the velocity of estimation. Recent studies have supported a theory which considers subitizing as a visual mechanism of pattern recognition, sensitive to spatial disposition of elements. These studies have found an increase in response rate and accuracy in the assessment of quantity when elements to be enumerated are arranged in an orderly fashion. Whether the numerosity of orderly arranged elements is accessed automatically, without the requirement of attentional resources, is a relevant issue not yet empirically investigated. The current study investigated the relation between subitizing and automaticity in a target detection task where distractors were non-symbolic number stimuli (dot patterns), with two different arrangements, random or canonical (like dice faces), having the same or different numerosity in the number target. We found that with canonical patterns, in the subitizing range, response times were faster in compatible trials, and slower in incompatible trials, compared to random patterns which did not influence response times in any condition. This result revealed that when elements in a visual display form easily recognizable patterns, their numerosity is accessed automatically.

Keywords: subitizing; pattern-recognition; attention

Introduction

When there is no time or opportunity to count the number of objects present in a visual scene, we still have the ability to detect their numerosity. As a matter of fact, according to behavioral and neuroimaging studies in the field of numerical cognition, humans and animals are equipped with an "approximate number system" (ANS) (Dehaene & Changeux, 1993; Halberda & Feigenson, 2008; Gilmore, Attridge, & Inglis, 2011), a mechanism which allows to extract the numerosity from a visual display (i.e., a group of dots) without the intervention of the explicit process of counting. Counting, indeed, is an accurate, slow and serial process focused on unities, while estimation is focused on the whole and proceeds in parallel. Thus, number estimation is both rapid and efficient, but, however, not errorless. In addition to these kinds of enumeration, there is another peculiar mechanism which allows quantifying sets of one up to about four unities, both immediately and with precision. The ability to detect, instantly and without errors, the numerosity of a small set of elements has been referred to as "subitizing" (from the Latin, subitus, immediately; Kaufman, Lord, Reese, & Volkmann, 1949). Since this mechanism cannot be identified neither with estimation nor with counting, its nature turns out to be controversial and still debated.

One hypothesis concerns the possible existence of a single mechanism of number estimation that is common to both small and large quantities and whose accuracy decreases as the amount of elements to enumerate increases. This mechanism would work according to the Weber's law, that is, based on a logarithmic scale (Balakrishnan & Ashby, 1992; Dehaene & Cohen, 1994) or a larger variability (Gallistel & Gelman, 2000). However, it has been proved that reaction times for estimation are different from those for subitizing, suggesting that they are distinct processes (Mandler & Shebo, 1982). Several recent studies, supporting this alternative hypothesis of two separate mechanisms, have found that estimation is pre-attentive and able to work for all numerosities, while subitizing has limited resources and is vulnerable to manipulations of attentional load (Egeth, Leonard, & Palomares, 2008; Olivers & Watson, 2008; Poiese Spalek, & Di Lollo, 2008; Railo, Koivisto, Revonsuo, & Hannula, 2008; Burr, Turi, & Anobile, 2010; Pincham & Szucs, 2012).

Subitizing has also been studied in the field of visual perception, in which researchers have investigated the role of information resulting from non-symbolic number stimuli (like dot patterns). They found a strong relationship between the perceptual features of the stimuli - like saliency, texture density, spatial arrangement, and covered area - and the ability to estimate their numerosity (Palomares & Egeth, 2010; Ross & Burr, 2010; Anobile, Cicchini, & Burr, 2014). These results are strong evidence against the hypothesis of a number system capable of working independently of the perceptual aspects of the stimulus, and support the hypothesis of subitizing as a more general sensory process rather than a specific number sense (Piazza, Fumarola, Chinello, & Melcher, 2011).

This hypothesis is in line with the classical theory by Trick and Pylyshyn (FINST, Fingers of INSTantiation; Trick & Pylyshyn, 1993, 1994), which defines subitizing as a non-numerical mechanism of spatial indexing, consisting of two stages: at the beginning, a spatial index is assigned to each object in the visual scene, through a pre-attentive and parallel bottom-up process; afterwards, a numeric label is assigned to every mapped index, through an explicit and serial top-down process. On one hand, this theory would explain the small range of subitizing since, in the first stage, the visual system can index a limited number of objects (between three and four) (Luck & Vogel, 1997); on the other hand, it would clarify that the differences in reaction times and the accuracy in judgments of numerosity are due to the controlled processes activated in the second stage.

Recent studies have investigated the conditions in which the subitizing range can be increased (e.g., Allen & McGeorge, 2008; Ashkenazi, Mark-Zigdon, & Henik, 2013; Gliksman, Weinbach, & Henik, 2016). Faster reaction times and low error rates have been observed, even besides the subitizing range, in enumeration tasks, when stimuli were canonical dot patterns, that is with symmetric, linear, or usually experienced configurations (i.e., dice faces), compared to randomly arranged dots. These results constitute evidence for the pattern recognition model of subitizing (Mandler & Shebo, 1982; Wolters, Van Hempen, & Wijlhuizen, 1987; Peterson & Simon, 2000; Logan & Zbrodoff, 2003; Krajcsi, Sbzaó & Mórocz, 2013; Jansen, Hofman, Straatemeier, Bers, Rajiimakers, & Maas, 2014). According to this model, spatial arrangements of one up to four elements create geometrical patterns, like a line between two dots, a triangle between three, and a quadrangle between four. As a result, quantities in the subitizing range are easily and quickly recognized thanks to the linear shapes created by elements. Hence, this phenomenon would be the result of a visual mechanism that encodes objects, within a visual display, as figures, and the more the objects show an orderly configuration, the faster and easier their recognition is. The decrease in reaction times and the increase of the subitizing range to more than four unities, with canonical patterns, support the theory of subitizing as a visual mechanism of pattern identification, since among the alternative hypotheses, like the FINST or the Weber estimation, this theory is the only one able to predict subitizing sensitivity to spatial disposition of elements. However, these researches on subitizing with canonical patterns have confined themselves to find an improvement in response time speed and accuracy in numerosity judgments without further investigating whether subitizing proceeds automatically with organized patterns.

According to studies that examined the relationship between subitizing and automaticity, subitizing shares attentional resources with the visual working memory, since its capacity can be reduced by a concurrent visuo-spatial task (e.g.: Railo et al., 2008; Vetter, Butterworth, & Bahrami, 2008; Egeth et al., 2008; Burr et al., 2010; Piazza et al., 2011; Pincham & Szucs, 2012). However, such studies only used dot patterns with a random spatial configuration as stimuli. Therefore, the main aim of the present study was to test if, with a canonical spatial configuration, the numerosity of non-symbolic number stimuli is accessed automatically, without the intention to enumerate and independently from temporal and visual attentional manipulations.

Our hypothesis was that when elements in a visual display form easily recognizable patterns, like those on dice faces, subitizing proceeds automatically. In order to test this hypothesis, a visual search task was designed, in which the target, an Arabic digit, had to be detected within a circular array, including a central dot pattern as a distractor [Fig.1]. The spatial configuration (random or canonical) of these distractor stimuli was manipulated and their numeric value was modified in order to be compatible or incompatible with the target Arabic digit. Our expectation was that in the compatible condition, when targets and distractors had the same numerical values, canonical patterns would generate shorter response times compared to when, in the same condition, distractors were random patterns. On the contrary, in the incompatible condition, when target and distractor had different numerical values, response times would be longer with canonical patterns. Thus, the general expectation was that only canonical patterns would facilitate or interfere with target detection because their numerical value is accessed automatically.

A specific expectation concerned differences in numerical range. Since in studies which have established that subitizing is not automatic, a discontinuity in response times between subitizing (faster RTs) and counting ranges (slower RTs) has been found (e.g., Pincham & Szucs, 2012), our expectation was to find the same discontinuity with random patterns. On the contrary, in the case of canonical patterns, no differences between ranges should occur, since, as we have seen before, subitizing range can increase above four with this kind of arrangement.

To sum up, the aim of this study was to examine whether subitizing works like a pattern recognition mechanism, that is, whether it is accurate and independent from attentional resources when the elements to be enumerated form easily recognizable patterns, even when the elements are more than four.

Methods

Participants

Forty-three undergraduate students (27 female, mean age 21.7, sd 6.4) participated in the experiment for course credit. All participants had normal color vision and normal or corrected-to-normal visual acuity. Informed, written consent was obtained at the beginning of the experiment.

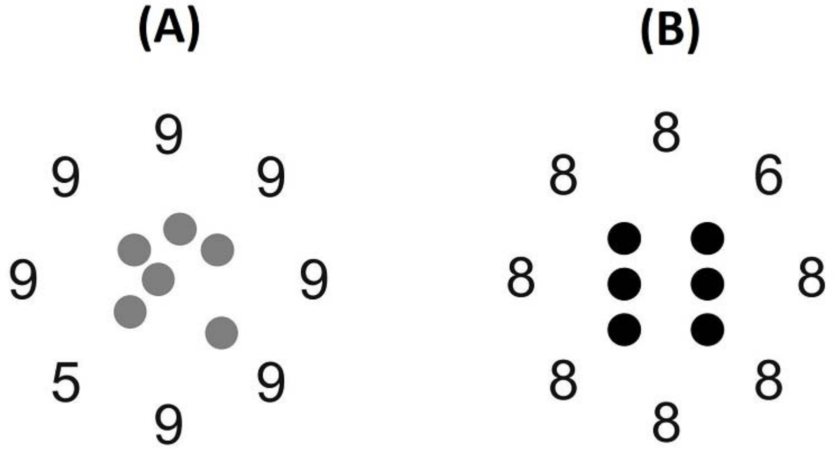

Figure 1. Examples of stimuli displayed in the main task: (A) trial in the incompatible condition, target “5”, non-target “9”, distractor with six dots, random arrangement, grey color; (B) trial in the compatible condition, target “6”, non-target “8”, distractor with six dots, canonical arrangement, black color. All combinations of target, non-target, dot color, dot arrangement, and condition were displayed in the main task.

Stimuli and apparatus

Stimuli were black circular visual search arrays presented on a white background. Arrays had eight Arabic digits equidistant from each other and from the center. In each array, one of the digit was a target (“2”, “3”, “4”, “5” or “6”) while the remaining were non-targets (all “8” or all “9”). Distractors were images of patterns of two, three, four, five or six dots. Dots were all grey or all black, all with the same diameter, presented on a white background, at the center of the arrays. The diameter of each dot was 1.1 cm. Patterns were created using two possible arrangements: canonical (like dice faces) or random, and they could be compatible (same numerosity) or incompatible (different numerosity) with the target digit. A total of 80 stimuli were designed (5 targets x 2 non-target x 2 dot colors x 2 dot arrangements x 2 conditions). All instructions and stimuli were presented on a VGA flat screen color computer monitor with 800 x 600 resolution at a refresh rate of 75 Hz.

Design and procedure

All participants were tested individually. They were seated in a quiet room at a comfortable viewing distance from the monitor. Full sessions were conducted using a dedicated computer program; responses were recorded by the same program; only a mouse (no keyboard) was provided to participants. Experimental sessions were divided into three stages: two warm-ups and a main task. In the first warm-up, participants practiced with the visual circular arrays without the distractors (10 stimuli). They were instructed to detect the target and click on a button with the corresponding digit, as quickly as possible. In the second warm-up, participants were requested to detect the target and the color (green or black) of the square shown at the center of the circular arrays (10 stimuli). This stage was made in order to avoid the possibility that participants did not attend the distractor stimuli (for a similar solution, see: Pincham & Szucs, 2012). In the main stage, participants had to detect the target digit and the color of the distractor dot patterns, and click on the corresponding buttons on the screen, right after. At the beginning of each trial, at the center of the monitor, a fixation cross (3.8 x 3.8 cm) was displayed for 1000 ms, followed by the circular array displayed for 150 ms. After the stimulus disappeared, response buttons were displayed: in the first warm-up, participants had to choose between two numbers (one was the target); in the second warm-up and in the main stage, after selecting the target, participants had to choose between the two distractors colors (grey or black). No time-limits were imposed and no feedback was provided. The order of trials within each stage was randomized, for each participant. In the main stage, trials were randomized in a way that the number of distractor dots to ignore in a trial never corresponded to the target number to detect in the subsequent trial. This presentation was controlled in order to avoid negative priming effects (Tipper, 1985), that could influence response times. The Simon effect (Simon & Rudell, 1967) was also controlled for response buttons: since the target digit could appear on the left or on the right of the circular array, response buttons were positioned vertically, one under the other, in order to avoid a spatial influence on the response. Dispositions (random/canonical) and conditions (compatible/incompatible) were counterbalanced for each numerosity (2,3,4,5,6).

Data Analysis

Only response times (RTs) from correctly responded trials about target numbers in the main stage were included in the analysis. For each participant, scores more than two standard deviations from mean were excluded as outliers (5.1%). A repeated-measures ANOVA was performed on data, with arrangement (canonical vs. random), condition (compatible vs. incompatible), and number range (subitizing vs. counting) as within subjects factors.

Results

There was a main effect of number range: on average, patterns with five and six dots slowed RTs (M = 1540) compared to patterns with two, three and four dots (M = 1491). Thus, contrary to the expectation, there was a difference between counting and subitizing ranges independently from arrangements (F(1,42) = 6.33, MSE = 32,801.68, $p<.02$, $\eta^2_p = .13$). We found a three-way interaction between arrangements, conditions and number ranges (F(1,42) = 17.54, MSE = 27,130.17, $p<.001$, $\eta^2_p = .29$). A post-hoc pairwise comparison (Bonferroni corrected) revealed differences between random and canonical patterns in the incompatible condition, for both subitizing and counting ranges, and in the compatible condition only for the subitizing range [Fig. 2]. In line with expectations, when distractors were canonical patterns in the subitizing range, RTs were faster (M = 1423.18) than when patterns were random (M = 1483.98) in the compatible condition ($p = .007$), and were slower (M = 1567.28) compared to when patterns were random (M = 1489.92), in incompatible conditions ($p = .033$). However, contrary to expectations, a different pattern of results was found for canonical dot patterns in the counting range (five and six dots): RTs were slower (M = 1436.48) compared to random patterns (M = 1519.28) in the incompatible condition ($p < .05$), while in the compatible condition no significant differences between arrangements resulted ($p = .114$).

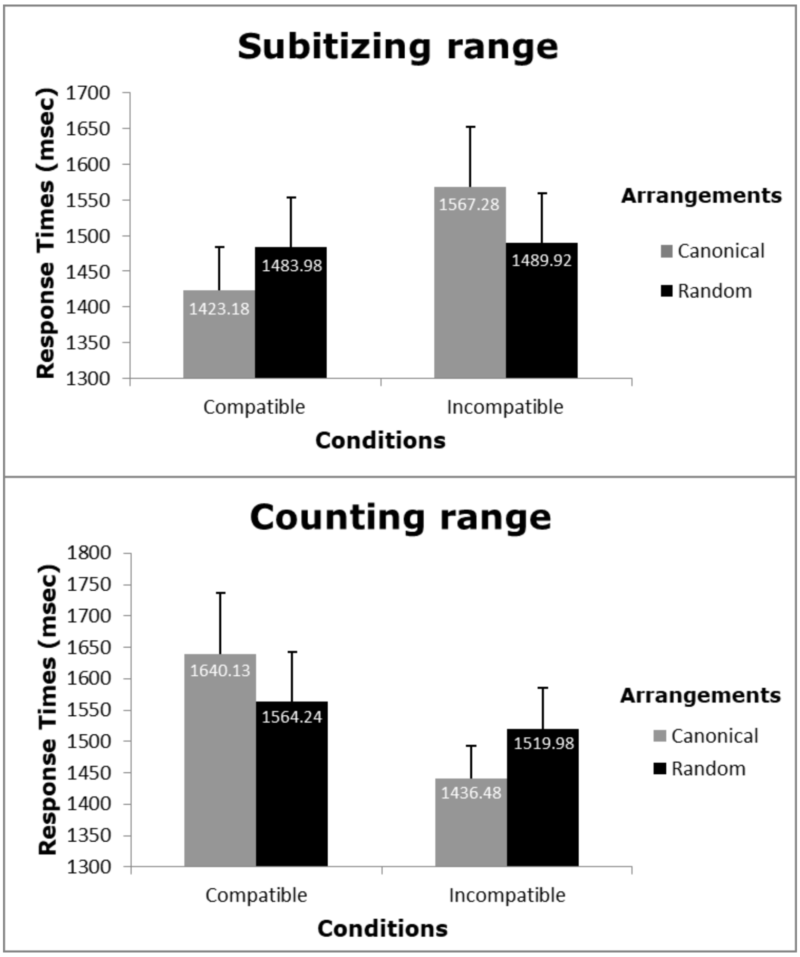

Figure 2. RTs differences between subitizing (2-4) and counting range (5-6), in compatible and incompatible conditions, by canonical and random dot patterns arrangements.

Discussion

The results of this experiment revealed that subitizing is automatic when groups of dots form canonical patterns (like dice faces). In a visual search task, the numerosity of canonical patterns was accessed automatically, facilitating or interfering with the detection of number target in compatible and incompatible conditions, respectively. On the contrary, when dots were arranged in a random way, their numerosity did not influence response times, in neither condition. This result is in line with previous findings in the literature on the non-automaticity of subitizing with random patterns (e.g., Egeth et al., 2008; Burr et al., 2010; Pincham & Szucs, 2012) and adds new evidence to the theory of subitizing working like a mechanism of pattern recognition (Mandler & Shebo, 1982). Indeed, in this experiment, we found that when elements form easily recognizable patterns their numerosity affected RTs in target detection. This result means that, since pattern stimuli lasted 150 ms, then their numerosity was accessed automatically. However, contrary to expectations, we did not found the same result when canonical patterns had more than four dots. Previous studies on canonical patterns have tested subitizing in enumeration tasks and have found that the ability to quickly and thoroughly enumerate a group of dots could increase to more than four unities when they are disposed in an orderly fashion (e.g., Ashkenazi et al., 2013; Krajcsi et al., 2013; Gliksman et al., 2016). This evidence lead us to assume that the increase in the range of subitizing revealed by these studies could be due to the ability of automatically recognize linear patterns, independently of their numerosity. Nevertheless, our results have shown that even if subitizing speed and accuracy can be improved with canonical patterns, this does not necessary imply that numerosities above its range are automatically recognized.

In our experiment response times were slowed down when canonical patterns had more than four dots in compatible conditions and speeded up in incompatible conditions. This is the opposite pattern of results we have found for dots within the subitizing range. We do not have a satisfactory explanation for this inversion, and we believe that it needs further investigation. However, since five and six dots patterns influenced response times, this can be interpreted at least as a consequence of the fact that their numerosity was somehow accessed, compared to random patterns which did not affect response times in any way.

Furthermore, this difference between counting and subitizing ranges suggests that the recognition of canonical patterns, like dice faces that we used, was not automated through the repeated experience of dices. In this case, indeed, patterns of five and six dots should have generated the same effect as the other numerosities, since all their dispositions were exactly like dice patterns. Thus, this difference between ranges seems to indicate that subitizing, as a pre-attentive visual pattern recognition mechanism, is sensitive to the spatial disposition of elements and can work without the requirement of attentional resources with a limited number of elements (up to four), when they are orderly arranged. Anyway, we believe that subitizing with canonical patterns should be further investigated in order to confirm its independence from attention. For example, it should be tested with linear configurations different from dice patterns, or in different experimental paradigms, like the attentional blink paradigm (Raymond, Shapiro & Arnell, 1992), in order to assess its pre-attentivity.

Conclusions

Subitizing is "to instantly know how many are", an important ability which has not only a numerical nature but involves also vision. We have shown that the spatial disposition of elements to be enumerated can improve this ability, and make it independent from attentional resources. Besides the theoretical issue, demonstrating that this ability can rely on an automatic visuo-spatial mechanism of pattern recognition, would have practical implications in the education field, like in the treatment of attentional deficits. For example, studies on children diagnosed with developmental dyscalculia (DD) have found that their difficulties in enumerating dot patterns, even in the subitizing range and even when they were canonically arranged, were due to their difficulties in recognizing patterns (Ashkenazi et al., 2013). In order to better understand the nature of these deficits, and their relation with visuo-spatial working memory resources, it should be useful to test DD participants with paradigms other than enumeration tasks, like the visual search task used in our study or the attentional blink paradigm.

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