Developmental and individual differences of gazing processes underlying the enumeration of small numbers

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小さい数の把握における注視プロセスの発達差と個人差

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要約

幼児 49 名（3 ～ 6 歳）と成人 75 名（18 ～ 23 歳）を対象として、小さい数（1 から 4）の計数課題を遂行中の眼球運動を測定し、小さい数把を行う際の注視プロセスの発達差と個人差を検討した。参加者は、キャンディ型ドットが 1 から 4 個配置されている刺激画面に対して、ドットの数を答えるように教示された。刺激画面は集中条件（ドットが画面中央に集中して提示される）と、分散条件（画面全体に分散して提示される）の 2 種類であった。ドットへの注視時間と注視パターンを分析した結果から、幼児はドットを一つひとつ目で追い注視して数把握をする傾向が明らかになった。また、成人は全体的にはドットを注視しない傾向にあったが、幼児のように一つひとつを注視する傾向にある者も存在した。この結果から、小さい数の把握は発達的に継時的処理から同時的処理に移行していくこと、サビタイジングとして捉えられてきた小さい数の把握は、発達的にはカウンティングが自動化されたものであること等が考察された。

Key words

enumeration, subitizing, gazing process, eye-movement, young children

1. Introduction

Subitizing, first described by Kaufman, Lord, Reese, & Volkmann (1949), is generally defined as a process of fast, confident and accurate enumeration of small collections of up to four items. Kaufman, et al. (1949) proposed that subitizing is a distinct process that can be distinguished from approximate estimation or exact counting, which are typically adopted for larger sets. Several studies measuring enumeration latencies (e.g., Chi & Klahr, 1975; Mandler & Shebo, 1982; Trick & Pylyshyn, 1994) have demonstrated that enumeration of small arrays (1-3 or 4 items) is fast and accurate, with a flat reaction time (RT) slope. In contrast, for large arrays of more than four items, both RTs and error rates increase sharply with a much steeper slope as a function of a set size. The process of subitizing small arrays is widely considered to be simultaneous, preverbal, and based more on acquired perceptual patterns than on number concepts (e.g., Trick & Pylyshyn, 1993; Trick & Pylyshyn, 1994), in contrast to enumeration of large arrays by counting.

Early developmental studies (Chi & Klahr, 1975; Svenson & Sjöberg, 1978) reported the existence of discontinuities in RT patterns in children between the enumeration of small sets and larger sets, similar to those found for adults. Chi & Klahr (1975) conducted a number counting task in which 5- to 6-year-old children and adults were asked to report the number of dots in an array, ranging from one to eight. The results revealed that, in both children and adults, two distinct quantification processes were used: a quick and accurate process for arrays of ≤ 3 dots and a slow and inaccurate process for arrays of ≥ 4 dots, with a steeper RT slope. However, the RT slope of children in the subitizing range was much steeper than that of the adults, which was almost flat. In Chi & Klahr (1975), it was unclear whether children's enumeration of small numbers (up to 3 items) was the same as adults' quick and accurate subitizing processing.

Some developmental researchers (Gelman & Gallistel, 1978; Gelman & Tucker, 1975) have expressed doubt about the claim that subitizing is a more primitive and automatic process of enumeration. Gelman & Gallistel (1978) reported that children count arrays even when enumerating small numbers of items (two or three items), while adults appeared to respond more automatically. That is, younger children (i.e., 2 or 3 years of age) exhibit a stronger tendency to count aloud when answering questions about the number of items. In addition, even 4- and 5-year-old children have been observed to count set sizes of two and three items, but did so rapidly and subvocally. Based on these findings, researchers asserted that young children first enumerate small numbers by verbal counting before taking advantage of perceptual grouping processes. Beckwith & Restle (1966) proposed that "perception of small numbers may be a skill developed by adults, a sort of shortcut to counting, rather than an elementary mental event" (Beckwith & Restle, 1966, p. 349). Gelman & Gallistel (1978) concluded that subitizing is a form of rapid counting and that the term should not be considered to represent a low-level, primitive way of abstracting the numerosity of a set.

However, subsequent research by Gallistel & Gelman (1991; 1992) examined the more primitive aspects of representing small numbers. Gallistel & Gelman (1991; 1992) considered subitizing to reflect a preverbal representation of numerosity without a number word. They divided adult numerical competence into two types: verbal and written representations of numerosity, and preverbal or nonverbal representations of numerosity, regarding the latter as a subitizing process. Overall, Gallistel & Gelman proposed that enumerating in the subitizing range is a more primitive process, unlike earlier conceptions of subitizing as an automatization of verbal counting.

Benoit, Lehalle, & Jouen (2004) examined the definitions of subitizing used in previous studies, noting that the underlying competence required varied between studies. Thus, they categorized subitizing into three types, according to task demands. First, in perceptual subitizing, individuals are required to distinguish perceptual arrays that differ by only one item (e.g., two dots and three dots). This type of differentiation may not be based on numerosity because many alternative cues such as the appearance of arrays can be used to produce a behavioral differentiation of habituation that has been observed in infant studies (e.g., Feigenson, Carey, & Hauser, 2002). Second, perceptual-preverbal subitizing (preverbal subitizing) requires the ability to distinguish small numbers of items numerously and independently of their perceptual appearance, but without the vocalization of number words. Thus, individuals are required to make a verbal or key-press response to an approximate number estimation in a dot-discrimination task, such as whether two arrays contain the same or a different number of dots (e.g., Starkey & Cooper, 1995). Third, in perceptual-verbal subitizing (verbal subitizing), number words are used to express numerosity. This is the original use of the word subitizing (Kaufman et al., 1949). In these tasks, individuals are asked to count aloud the number of dots in an array (i.e., dots-counting task).

In the current study, we focused on the process of verbal subitizing in both young children and adults, and re-examined the developmental changes underlying the ability to enumerate small numbers of items. According to Benoit et al.'s (2004) categorization described above, the discrepancy in the conception of subitizing between Gelman & Gallistel (1978) and Gallistel & Gelman (1991; 1992; 2000) can be interpreted as a shift in the different aspects of subitizing, from verbal subitizing to perceptual or preverbal subitizing. The latter process of subitizing without number words has been addressed in the context of the core systems or approximate number system, which has mainly been examined in infant studies (Feigenson et al., 2002; Feigenson, Dehaene, & Spelke, 2004; Halberda & Feigenson, 2004; Hyde & Spelke, 2011). However, regarding verbal subitizing, the process of traditional subitizing with number words, it remains unclear whether Gelman & Gallistel's (1978) early hypothesis is accurate, predicting that young children first count small numbers (i.e., 2 or 3) vocally or subvocally before taking advantage of perceptual grouping processing, whereas subitizing by adults is an automatization of verbal counting.

Although few studies have examined verbal subitizing in young children, Benoit et al. (2004) examined whether young children process small numbers of dots with number words through a sequential process of counting as a one-by-one indexing of items, or via a simultaneous process of subitizing, in which items are grasped as a whole. In their experiment, 3-, 4- and 5-year-old children were asked to report the number of dots in an array (ranging from 1 to 6) presented under two conditions. In the simultaneous-presentation condition, all elements in the collection were displayed simultaneously, while in the consecutive-presentation condition, each element was displayed sequentially. The results revealed that 3-year-olds performed better in the simultaneous than the consecutive condition. However, in 5-year-olds, no difference was observed between the conditions. Benoit et al. (2004) concluded that younger children first acquire small numbers through the simultaneous process of verbal subitizing without counting one by one, and that verbal subitizing is a more primitive process than counting.

However, concluding that the simultaneous process of subitizing is the predominant method of enumerating small numbers of items in younger children would be premature, because the low level of performance in the consecutive-presentation condition in 3-year-olds observed by Benoit et al. (2004) does not directly indicate that young children acquire small numbers simultaneously without counting each dot. In the simultaneous task, the children were asked to report the number of items only once. Conversely, in the consecutive task, they were required to react to both consecutive counting (i.e., serial counting of dots vocally) and consecutive cardinality (i.e., cardinal naming after serial counting). Therefore, 3-year-olds were likely to experience difficulty counting dots that consecutively disappeared and finally stated the cardinal number as a whole because of the immaturity of their executive functioning, including working memory (e.g., Carlson, 2006). In addition, better performance under the simultaneous-presentation condition does not necessarily mean that dots were processed in an array simultaneously, and it remains unclear whether young children process small numbers without counting as a one-by-one indexing of items.

Recent studies of dyscalculia in elementary school children (Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009; Schleifer & Landerl, 2011) suggested that individuals with dyscalculia need to compensate for impaired subitizing ability by applying a serial counting process, even for small number ranges. For example, Schleifer & Landerl (2011) compared RTs between typically developing and dyscalculic children aged 8, 9 and 12 years using a simple dot-counting task. The results revealed that dyscalculic children exhibited RT slopes that were twice as steep as the control group in subitizing ranges of 1-3, whereas no differences between the two groups were observed in the counting ranges of 4-7. Schleifer & Landerl (2011) reported that dyscalculic children performed serial counting even in the subitizing range. Thus, studies of dyscalculic children have indicated that serial counting might be a premature or not fully developed form of calculating small numbers of items.

However, the data in these studies have typically been based on RTs, which do not directly show serial attention processing when counting small numbers of items.

Several previous studies in adults examined differences in attentional processes during enumeration of small versus large numbers of items (Railoa, Koivistoa, Revonsuoa, & Hannulae, 2008; Sophian & Crosb, 2008; Trick & Pylyshyn, 1993; 1994; Watson, Maylor, & Bruce, 2007). These studies have consistently suggested that subitizing for small number ranges in adults does not require serial attention, unlike counting for large number ranges. Trick & Pylyshyn (1993; 1994) investigated RTs and examined the different levels of visual processing between subitizing and counting, including the spatially parallel, preattentive stage of visual analysis (i.e., feature registration or grouping) for subitizing, and the spatially serial, attentive stage of visual analysis for counting. Recent studies have investigated eye movements during dot counting as an indicator of parallel preattentive or serial attentive processes (Sophian & Crosb, 2008; Watson et al., 2007). Sophian & Crosb (2008) reported that eye fixations were less likely to be located in arrays of ≤ 3 items than in arrays of ≥ 4 items, and that the fixation times for arrays of large numbers increased as a function of the number of dots. These eye-movement data confirmed that the enumeration of very small sets in adults requires parallel preattentive process and do not depend on serial attentive processes of counting.

Another eye-movement study in adults by Li, Logan, & Zbrodoff (2010) tested several hypotheses regarding the coupling between eye movements and enumeration while adults enumerated a large number of dots (5 to 12 dots). The indexing hypothesis assumes one-by-one coupling (i.e., tight coupling) between eye movements and the underlying counting process, in which eye movements implement the process of indexing objects in the display. The perception hypothesis assumes fewer fixations of dots (i.e., looser coupling), with eye movements directed to dense, central regions of the display. Gaze analysis revealed that adults fixated on approximately half of the total number of dots on the display, consistent with the perception hypothesis. The results suggested that adults depend on preattentive processing, not only in the subitizing range, but also when enumerating over the subitizing range.

In the current study, we examined differences in gazing processes between young children and adults when enumerating small numbers, using eye movement data as an index of parallel and serial processing. The abovementioned studies of dyscalculia in elementary school children and adults imply two different gazing processes during the enumeration of dots even in small numbers: parallel or preattentive processes and serial or one-by-one attentive processes. The former indicates that eye fixations are less likely to be located in each dot, whereas the latter reflects one-by-one fixation on each dot. In addition, earlier studies (Beckwith & Restle, 1966; Gelman & Gallistel, 1978), suggest that individual differences in processing could be observed in enumeration for small numbers. However, to the best of our knowledge, no previous study has investigated developmental and individual differences in gazing patterns during a dot-counting task between young children and adults.

In the current study, we prepared two types of dot-array presentations (i.e., a convergent condition and a distributed condition) to assess gazing patterns when enumerating, using eye movements. Previous studies using eye movement data (e.g., Railoa et al., 2008; Watson et al., 2007) have located dot stimuli within narrow regions with visual angles of approximately ≤ 10°, and analyzed fixation durations for the whole area, including all dots. However, using this paradigm, an increase in fixation duration does not necessarily distinguish fixation upon each object or sserial attention when processing dots one by one. Therefore, we presented dots that were distributed across a wider area, within 25°, based on Gelman & Tucker's (1975) study, in which no differences were observed regarding counting performance in young children between visual angles of 1.7°-5.4° vs. 25.4°. The distributed condition enabled us to analyze gazing patterns for each dot and provided an indicator of parallel or simultaneous processing.

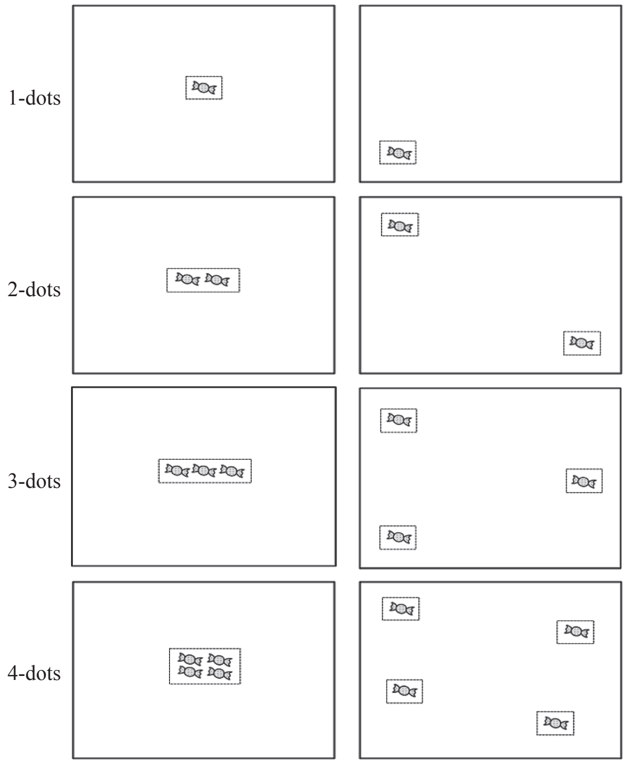
2. Methods

2.1 Participants

Forty-nine preschool children (27 boys and 22 girls, aged 3:6-6:6, M = 5:4) from a Japanese kindergarten, and 75 Japanese undergraduate students (28 men and 47 women, aged 18:0-23:0, M = 18:6) participated in this experiment. We initially recruited 61 children and 84 adults. However, 12 children and 9 adults were excluded because of unsuccessful calibration of eye-tracking monitoring. For the children, the purpose and method of the study were explained to the head administrators and class teachers of their school, as well as to their parents, who gave permission for participation. The undergraduate students participated in the experiment as part of a psychology class. They were provided with an explanation of the purpose of the experiment after giving their consent to participate.

2.2 Materials

The stimuli were eight patterns of collections of 1-4 candy-shaped dots, as presented in Figure 1. Each dot was 100 × 50 pixels in size (approximately 3.3 × 1.7 cm on the display) and the collections were displayed on a white background that was 1000 × 750 pixels in size (approximately 33 × 26 cm). Under the convergent condition, all dots were presented in a central screen area of 9.4° × 4.2° (approximately 9.8 × 4.3 cm), while in the distributed condition, each dot was presented separately in an area of 24.8° × 18.38° (approximately 26.3 × 19.3 cm). We prepared four patterns (i.e., 1-4 dots) in each condition, as shown in Figure 1. In addition, we indicated the center of the display with a white fixation cross on a black background, which was presented immediately before each stimulus.



(a) Convergent condition (b) Distributed condition

Figure 1: Stimuli used in this experiment

Note: The areas within dot-line squares are AOIs.

2.3 Procedure

Participants were shown eight images (see Figure 1) and asked to report the number of candy-shaped dots that appeared on the monitor. No practice trials were given, and only eight test trials were conducted because Li et al. (2010) reported that, if participants enumerate the same or similar displays many times, counting may be replaced by memory retrieval.

All stimuli were presented using a Tobii T60 eye tracker (Tobii Technology, Stockholm, Sweden), with Tobii Studio 2.1 software for managing experiments and collecting data. The stimuli were displayed at a resolution of 1024 × 768 pixels on a Tobii T60 17-inch monitor. Participants were seated in front of the monitor, which was set approximately 60 cm away from the eyes. We used five-point calibration for the eye-tracking system, in which participants were required to attend sequentially to animation character pop-ups that appeared at one of five different locations (the four corners and the center) on the monitor.

After successful calibration, the experimenter gave the instructions “Now, I am going to show you some candies. Please tell me how many candies appear on the monitor” and started the session. Each stimulus presentation was followed by presentation of a fixation cross at the center of the screen for 1 second. The presentation order for the eight stimuli was randomized for each participant. The fixation duration prior to the participant’s response was measured by the experimenter, who pressed the reaction keys assigned to true or false answers as soon as the participant made a verbal response. Thus, the duration was defined as the time from the appearance of the stimulus to the time at which the reaction key was pressed. We used this procedure because young children are known to experience difficulty operating response keys. When the reaction key was pressed, the display immediately turned black. The experimenter presented the next stimulus at an individualized pace.

3. Results

All 75 adults accurately counted all eight stimuli. Under the distributed condition, one child miscounted the 2-dot stimuli, one child miscounted the 3-dot stimuli, and two children miscounted the 4-dot stimuli. However, these four children miscounted only once out of eight trials. Therefore, the data of these four participants were included in the following eye movement analysis based on an adequate amount of data.

Eye positions per approximately 16 msec and response times were recorded using a Tobii T60 eye tracker (Tobii Technology, Stockholm, Sweden) with Tobii Studio 2.1 software for managing experiments and collecting data. Using a fixation-filter radius (i.e., threshold value) of 25 pixels, fixation durations were computed for the whole stimulus area (1000 × 750 pixels) and the areas of interest (AOIs) of the candy-shaped dots (see Figure 1). The threshold value sets the maximum value regarding how far apart fixations were allowed to be in terms of pixel radius while still belonging to the same fixation. If fixation moved to the outside of the threshold radius, it was classified as a saccade. The AOIs were defined as areas where dots were surrounded by a 25-pixel margin. Four AOIs for the convergent condition, and 10 AOIs for the distributed condition were extracted. Mean fixation durations and standard deviations (SDs) for the whole area and each AOI was calculated according to age, and the values over the mean plus 3 SDs were omitted as outliers from the data. The outliers comprised 44 out of 2728 data.

3.1 Fixation duration analysis

Figure 2 (Table 1) shows the mean fixation duration of the whole area as a function of age (i.e., children and adults), condition (i.e., convergent and distributed), and the number of dots (i.e., 1, 2, 3, and 4). We conducted a three-way (two age groups × two conditions × four stimuli type) ANOVA on the mean durations. The main effects of age (F (1,96) = 198.81, $\eta p^2 = .674$, $p < .01$), condition (F (1,96) = 29.05, $\eta p^2 = .232$, $p < .01$), and stimuli type (F (3,288) = 17.16, $\eta p^2 = .152$, $p < .01$) were significant. These results indicated that the durations for the children were longer than those for the adults, and that the durations under the distributed condition were longer than those for the convergent condition. The interaction between age and stimuli type was significant (F (3,288) = 13.47, $\eta p^2 = .123$, $p < .01$). The significant simple main effect in children (F (3,288) = 30.37, $\eta p^2 = .240$, $p < .01$), and multiple comparisons revealed that the children spent a longer time looking at a 3-dot than a 1-dot stimuli ($t = 2.72$, $p < .01$), and that they spent a longer time looking at a 4-dot than a 3-dot stimuli ($t = 5.03$, $p < .01$). In contrast, the adults' duration times were the same for all types of stimuli.

Figure 3 (Table 2) shows the mean fixation duration of AOIs as a function of an age condition, and the number of dots. For the 2-, 3- and 4-dot stimuli in the distributed condition, fixation durations were defined as the sum of the total durations of all dots on the stimulus. We conducted a three-way (two age groups

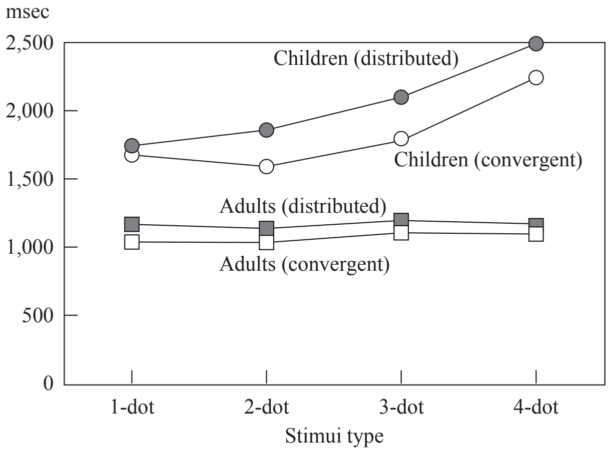


Figure 2: Mean fixation duration for whole area as a function of age and display condition

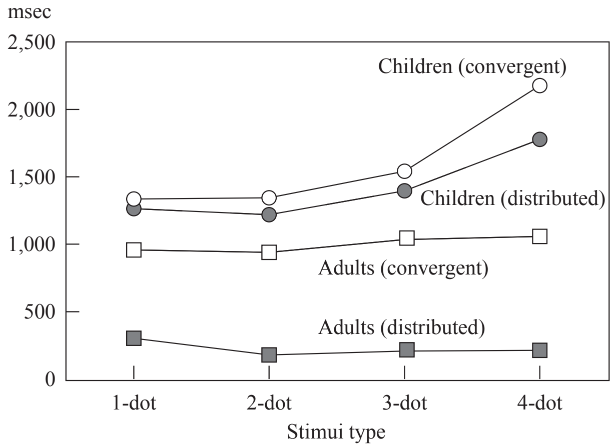


Figure 3: Mean fixation duration for AOIs as a function of age and display condition

Table 1: Mean fixation duration as a function of age, condition, and stimuli type (Whole area)

		Children (n = 41)					Adults (n = 57)				
Display condition	Stimuli	*M*	*SD*	*SE*	95 % CI		*M*	*SD*	*SE*	95 % CI	
					LL	*UL*				*LL*	UL
Convergent	1-dots	1676	610	95	1543	1809	1037	228	30	924	1150
	2-dots	1591	476	74	1479	1703	1034	249	33	939	1129
	3-dots	1780	490	77	1672	1887	1104	188	25	1013	1196
	4-dots	2243	1133	177	2012	2474	1097	186	25	901	1293
Distributed	1-dots	1743	535	84	1629	1856	1168	164	22	1071	1264
	2-dots	1859	660	103	1718	2001	1137	215	28	1017	1257
	3-dots	2100	615	96	1970	2230	1196	175	23	1086	1306
	4-dots	2491	1113	174	2263	2718	1170	198	26	977	1363

Note. CI = confidence interval; *LL* = lower limit, *UL* = upper limit.

Table 2: Mean fixation duration as a function of age, condition, and stimuli type (AOIs)

		Children (n = 41)					Adults (n = 57)				
Display condition	Stimuli	*M*	*SD*	*SE*	95 % CI		*M*	*SD*	*SE*	95 % CI	
					LL	*UL*				*LL*	*UL*
Convergent	1-dots	1335	717	112	1175	1496	958	305	40	822	1094
	2-dots	1345	541	85	1213	1478	940	321	43	828	1052
	3-dots	1542	619	97	1402	1682	1034	276	37	915	1153
	4-dots	2177	1186	185	1934	2420	1058	218	29	852	1264
Distributed	1-dots	1263	588	92	1127	1400	304	295	39	187	420
	2-dots	1220	671	105	1071	1369	179	273	36	52	305
	3-dots	1396	725	113	1236	1557	209	292	39	72	345
	4-dots	1778	990	155	1571	1985	214	254	34	38	389

Note. CI = confidence interval; *LL* = lower limit, *UL* = upper limit.

× two conditions × four stimuli type) ANOVA on the mean durations. The main effects of age (F (1,96) = 176.41, $\eta p^2 = .648$, $p < .01$), condition (F (1,96) = 173.72, $\eta p^2 = .644$, $p < .01$), and stimuli type (F (3,288) = 19.37, $\eta p^2 = .168$, $p < .01$) were significant. These results indicated that the durations for the children were longer than those for the adults and that the durations under the distributed condition were shorter than those for the convergent condition. Moreover, the interactions between age and condition were significant (F (1,96) = 65.15, $\eta p^2 = .404$, $p < .01$). Additionally, the simple main effects of condition were significant in children (F (1,96) = 13.05, $\eta p^2 = .119$, $p < .01$), and in adults (F (1,96) = 225.86, $\eta p^2 = .701$, $p < .01$), but adults tended to spend a shorter amount of time fixating for the distributed condition compared with children. Interactions between age and stimuli type were significant (F (3,288) = 15.28, $\eta p^2 = .137$, $p < .01$). The significant simple main effect in children (F (3,288) = 34.24, $\eta p^2 = .263$, $p < .01$), and multiple comparisons revealed that children spent the longest time looking at 4-dot stimuli (1-dot: $t = 8.01$, $p < .01$, 2-dot: $t = 8.21$, $p < .01$, 3-dot: $t = 6.00$, $p < .01$) and that there was no difference in the amount of time spent fixating among the three types of stimuli. However, adults spent the same amount of time fixating for all stimuli types.

3.2 Gazing pattern analysis

The ANOVA revealed a considerable difference in the durations under the distributed condition between children and

Table 3: The number and percentage of each gazing pattern (1-dot stimulus)

		Gazing pattern		Total
		0	1	
Children	*n* (%)	3 (6.1)	46 (93.9)	49 (100.0)
	r	–3.41**	3.41**	
Adults	*n* (%)	24 (32.0)	51 (68.0)	75 (100.0)
	r	3.41**	–3.41**	

Note: *r* = adjusted residual; ** $p < .01$.

Table 4: The number and percentage of each gazing pattern (2-dot stimulus)

		Gazing pattern			Total
		0	1	2	
Children	*n* (%)	1 (2.1)	9 (18.8)	38 (79.2)	48 (100.0)
	r	–5.99**	–0.92	6.52**	
Adults	*n* (%)	40 (54.8)	19 (26.0)	14 (19.2)	73 (100.0)
	r	5.99**	0.92	–6.52**	

Note: *r* = adjusted residual; ** $p < .01$.

Table 5: The number and percentage of each gazing pattern (3-dot stimulus)

		Gazing pattern				Total
		0	1	2	3	
Children	*n* (%)	2 (4.2)	7 (14.6)	17 (35.4)	22 (45.8)	48 (100.0)
	r	–5.02**	–2.08*	1.67	6.27**	
Adults	*n* (%)	33 (47.1)	22 (31.4)	15 (21.4)	0 (0.0)	70 (100.0)
	r	5.02**	2.08*	–1.67	–6.27**	

Note: *r* = adjusted residual; ** $p < .01$, * $p < .05$.

Table 6: The number and percentage of each gazing pattern (4-dot stimulus)

		Gazing pattern					Total
		0	1	2	3	4	
Children	*n* (%)	1 (2.1)	1 (2.1)	13 (27.7)	18 (38.3)	14 (29.8)	47 (100.0)
	r	–5.21**	–4.06**	1.40	4.84**	4.73**	
Adults	*n* (%)	31 (47.0)	22 (33.3)	11 (16.7)	2 (3.0)	0 (0.0)	66 (100.0)
	r	5.21**	4.06**	–1.40	–4.84**	–4.73**	

Note: *r* = adjusted residual; ** $p < .01$.

adults; i.e., adults' tendency to spend a short amount of time fixating on stimuli. Next, gazing patterns were analyzed in detail under the distributed condition. This was done by categorizing the participants into two to five fixation-pattern groups for each stimulus. For the 1-dot stimulus, two patterns were found (i.e., 0: no gazing, 1: gazing at 1 dot). In the same manner, we categorized participants into one of three pattern groups for the 2-dot stimulus (i.e., 0: no gazing, 1: gazing at 1 dot, 2: gazing at 2 dots), then they were categorized into one of four and five pattern groups for the 3-dot stimulus and the 4-dot stimulus, respectively. Tables 3-6 show the percentages of the gazing patterns as a function of age. We conducted a χ^2 test and adjusted the residual analysis for each stimulus. Results revealed that the proportions of the gazing patterns significantly varied with age for all stimuli (1-dot stimulus: $\chi^2 = 11.65$, $df = 1$, $p < .01$, 2-dot stimulus: $\chi^2 = 48.65$, $df = 2$, $p < .01$, 3-dot stimulus: $\chi^2 = 55.15$, $df = 3$, $p < .01$, and 4-dot stimulus: $\chi^2 = 73.13$, $df = 4$, $p < .01$). The values of adjusted residuals are shown in Tables 3-6. These results showed that children tended to fixate on more than one dot or consecutively on each dot, while adults were unlikely to look at any dots or to fixate on only one dot.

To clarify individual differences in gazing patterns, the total sum of gazing points for all four stimuli (min = 0, max = 10) was calculated for each participant. The percentages of each pattern as a function of age is shown in Figure 4. The pattern observed in the adults varied from 0 to 8, and the pattern in the children varied mainly from 5 to 10. Approximately 18 % of the adults attended to ≥ 5 points, with two adults (3.4 %) attending to 7 or 8 points, which was the same category as that for the majority of the young children. Only one child (2.2 %) showed the adult-like pattern of not fixating on any dots; however, this participant did not look at any AOIs even in the convergent condition, unlike all other participants. Therefore, it was assumed that this data reflected an idiosyncratic pattern of eye movements.

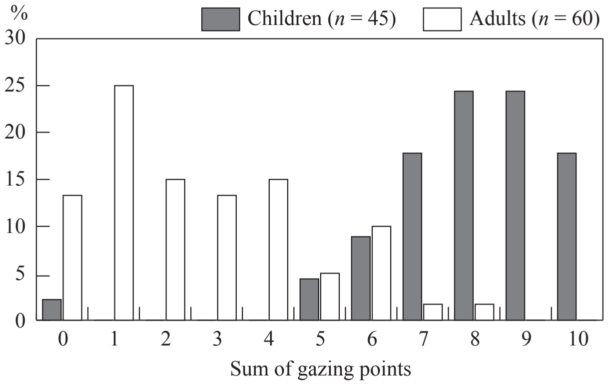


Figure 4: Percentages for each gazing pattern as a function of age (sum of all stimuli)

4. Discussion

The analysis of fixation durations revealed a typical developmental tendency for longer durations and steeper slopes in children, in accordance with previous studies (Chi & Klahr, 1975; Svenson & Sjöberg, 1983). In the current study, the duration difference between children and adults ranged from approximately 500 to 700 msec for 1-, 2-, and 3-dot stimuli in the convergent condition. In addition, children exhibited a steeper slope between 3-dot and 4-dot stimuli, in contrast to the flat slope exhibited by adults. These developmental differences in duration were also observed in RT data between 5- and 6-year-olds and adults reported by Chi & Klahr (1975), which confirmed that young children are able to respond quickly to arrays of up to three items.

Although the whole-area durations in the distributed condition were longer than those in the convergent condition, for fixation duration around the dot areas, shorter durations were observed in the distributed condition compared with the convergent condition. This result might be partially explained by the fact that, under the convergent condition, all dots were presented around the center of the display where the fixation cross appeared immediately before the presentation of each stimulus. However, adults tended to attend for substantially less time in the distributed condition, whereas only slight differences between the two conditions were observed in children. These results suggest that adults maintained fixation on the central area even when the dots were distributed in space. In contrast, children moved their eyes to the area in which the dots were located.

The gazing patterns under the distributed condition revealed that children tended to fixate on more than one dot, or on each dot one by one, while adults were unlikely to look at any dots, or fixated on only one dot. The children's eye movement data indicated that young children tended to associate small numbers of dots with number words through a serial process of counting, rather than a parallel process of subitizing. This finding is not in accord with Benoit et al.'s (2004) proposal that the simultaneous process of verbal subitizing is more primitive and predominant for young children. However, Gelman & Gallistel (1978) reported that 2- and 3-year-olds have a strong tendency to count aloud, and that even 4- and 5-year-olds count small arrays, but do so rapidly and subvocally. The eye fixation patterns we observed in the children may have reflected the rapid and subvocal process of one-by-one counting.

The finding that young children initially depended on fixating on each dot for enumeration may explain the results observed in several previous studies examining the effect of "grouping" (e.g., Ashkenazi, Mark-Zigdon, & Henik, 2012; Starkey & McCandliss, 2014). Starkey & McCandliss (2014) compared enumeration speeds when counting 5-, 6-, 7-dot arrays in unstructured-dots and grouped-dots conditions for four age groups (i.e., young children, first, second, and third graders).

The grouped arrays were displayed as a collection of subsets in the subitizing range (i.e., three subgroups of 1-3 items). For example, five dots were arranged into two subsets of 2-dot and 1-dot arrays. The results revealed no difference in RTs between the two conditions in the youngest group, while the first to third graders spent less time counting grouped arrays. The youngest children were likely to attend to 2- or 3-dot arrays sequentially within the subset in the same manner observed in the unstructured condition. In contrast, elementary school children were able to acquire small numbers of dots within a subset through pre-attentive or simultaneous processing.

In addition, the enumeration speed among young children and first graders increased as a function of the number of items for both conditions. However, in second and third graders, the tendency to increase with the set size for the grouped-dots condition was not observed. This finding corresponded with our data showing that the impact of a set size was dependent on age group: children spent longer looking at 3- or 4-dot arrays, while adults spent the same amount of time, irrespective of the number of dots. These results suggest that, with age, the serial process by which a longer amount of time is required is gradually replaced by a more developed form of parallel processing that takes a shorter amount of time.

Although an overall developmental tendency to shift from sequential to parallel processing was observed, individuals' gazing patterns widely varied from 0 to 8 in adults and from 5 to 10 in children. In particular, two adults (3.4 %) enumerated small numbers by fixating on almost every dot. A similar atypical pattern of fixation in adults was reported in several previous studies examining arithmetic skills in dyscalculic adults (e.g., Bruandet, Molko, Cohen, & Dehaene, 2004; Butterworth, 1993). Bruandet et al. (2004) compared counting skills between dyscalculic women with Turner syndrome and a control group, reporting that the dyscalculic group consistently exhibited slower RTs than controls for counting even two-dot arrays, suggesting that dyscalculic adults serially count, even in the subitizing range. Although this RT data did not directly measure a gaze pattern of tight coupling, the dyscalculic participants might share similar processing for small numbers as the rare cases of tight coupling by adults observed in the current study.

The developmental changes and individual differences from tight to loose coupling of eye movements and enumerations observed in the current study suggest that subitizing is a rapid and automatic form of serial counting, as proposed by Gelman & Gallistel (1978), or a skilled shortcut for counting, which is practiced during development (Beckwith & Restle, 1966). Subitizing or enumerating small numbers of items by adults has traditionally been considered to be a spatially parallel and preattentive process (e.g., Trick & Pylyshyn, 1993; Trick & Pylyshyn, 1994). However, recent studies have raised doubts about this view, because the enumeration of small sets has been observed to also be affected by attentional limitations, although it is less dependent on attentional processes compared with the processing of large sets (Pincham & Szuücs, 2012; Sophian & Crosb, 2008; Railoa et al., 2008). These studies in adults indicate that enumeration of both small and large numbers share the same processes of counting, and the former process (i.e., subitizing) reflects the less-attentive and automatic form of serial counting, which gradually develops from early childhood to adulthood.

Recent studies have implied the existence of a process related to the emergence of automatization of sequential counting. Piazza, Fumarola, Chinello & Melcher (2011) examined the relationship between adult performance in two different enumeration tasks (the dot-counting task and the dot-comparison task) and visual working memory (VWM). The results revealed that only performance on the counting task was correlated with VWM capacity. In addition, a correlation between the counting and discrimination tasks was not observed, in accordance with previous findings (Revkin, Piazza, Izard, Cohen, & Dehaene, 2008). These findings suggest that a developmental shift to rapid and automatic counting may rely on the growth of the VWM during childhood.

The current study involved limitations that should be considered, suggesting several potential research directions. First, the features of developmental changes from consecutive to simultaneous processing remain to be clarified. While the current study revealed the different processes involved in enumerating small numbers between young children and adults, it remains unclear when these changes emerge, and what individual or general factors affect the shift to less-attentive and automatic processing. Second, differences of gazing processes between preverbal and verbal subitizing should be examined in future research. In the current study, we focused on verbal subitizing, in which number words were used in enumerating dot arrays. Thus, it will be necessary for future studies to examine the gazing process of preverbal subitizing, involving approximate number estimation in discrimination tasks to determine whether two arrays (e.g., 2 vs. 3) contain the same or a different number of dots. For example, if young children show a tendency to fixate on each dot one by one even in discrimination tasks, this would suggest that preverbal and verbal subitizing share the same counting processes. Finally, a fundamental problem of interpreting eye movement data should be considered. It is possible that sequential attention does not reflect the cognitive process of counting one by one. Thus, other indices, such as brain activity, should be used in future studies to clarify the underlying cognitive process of consecutive and simultaneous enumeration processes.

References

Ashkenazi, S., Mark-Zigdon, N., & Henik, A. (2012). Do subitizing deficits in developmental dyscalculia involve pattern recognition weakness? *Developmental Science*, 16, 35-46.

Beckwith, M. & Restle, F. (1966). Process of enumeration. *Psychological Review*, 73, 437-444.

Benoit, L., Lehalle, H., & Jouen, F. (2004). Do young children acquire number words through subitizing or counting? *Cognitive Development*, 19, 291-307.

Bruandet, M., Molko, N., Cohen, L., & Dehaene, S. (2004). A cognitive characterization of dyscalculia in Turner syndrome. *Neuropsychologia*, 42, 288-298.

Butterworth, B. (1993). *The mathematical brain*. London: Macmillan.

Carlson, S. M. (2005). Developmentally sensitive measures of executive function in preschool children. *Developmental Neuropsychology*, 28, 595-616.

Chi, M. T. H. & Klahr, D. (1975). Span and rate of apprehension in children and adults. *Journal of Experimental Child Psychology*, 19, 434-439.

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object files versus analog magnitudes. *Psychological Science*, 13, 150-156.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, 8, 307-314.

Gallistel, C. R. & Gelman, R. (2000). Non-verbal numerical cognition: From reals to integers. *Trends in Cognitive Sciences*, 4, 59-65.

Gallistel, C. R. & Gelman, R. (1991). The preverbal counting process. In W. Kessen, A. Ortony, & F. I. M. Craik (eds.), *Thoughts, memories and emotions: Essays in honor of George Mandler* (pp. 65-81). Hillsdale, NJ: Erlbaum.

Gallistel, C. R. & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, 44, 43-74.

Gelman, R. & Gallistel, C. (1978). *The child's understanding of number*. Cambridge, MA: Harvard University Press.

Gelman, R. & Tucker, M. F. (1975). Further investigations of the young child's conception of number. *Child Development*, 46, 167-175.

Halberda, J. & Feigenson, L. (2004). Developmental change in the acuity of the "number sense": The approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, 44, 1457-1465.

Hyde, D. C. & Spelke, E. S. (2011). Neural signatures of number processing in human infants: Evidence for two core systems underlying numerical cognition. *Developmental Science*, 14, 360-371.

Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkmann, J. (1949). The discrimination of visual number. *American Journal of Psychology*, 62, 498-525.

Li, X., Logan, G. D., & Zbrodoff, N. J. (2010). Where do we look when we count?: The role of eye movements in enumeration. *Attention, Perception, & Psychophysics*, 72, 409-426.

Mandler, G. & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General*, 111, 1-22.

Moeller, K., Neuburger, S., Kaufmann, L., Landerl, K., & Nuerk, H.-C. (2009). Basic number processing deficits in developmental dyscalculia: Evidence from eye tracking. *Cognitive Development*, 24, 371-386.

Piazza, M., Fumarola, A., Chinello, A., & Melcher, D. (2011). Subitizing reflects visuo-spatial object individuation capacity. *Cognition*, 121, 147-153.

Pincham, H. L. & Szücs, D. (2012). Intentional subitizing: Exploring the role of automaticity in enumeration. *Cognition*, 124, 107-166.

Railoa, H., Koivistoa, M., Revonsuoa, A,, & Hannulae, M. M. (2008). The role of attention in subitizing. *Cognition*, 107, 82-104.

Revkin, S. K., Piazza, M., Izard, V., Cohen, L., & Dehaene, S. (2008). Does subitizing reflect numerical estimation? *Psychological Science*, 19, 607-614.

Schleifer, P. & Landerl, K. (2011). Subitizing and counting in typical and atypical development. *Developmental Science*, 14, 280-291.

Sophian, C. & Crosb, M. E. (2008). What eye fixation patterns tell us about subitizing. *Developmental neuropsychology*, 33, 394-409.

Starkey, G. S. & McCandliss, B. D. (2014). The emergence of "groupitizing" in children's numerical cognition. *Journal of Experimental Child Psychology*, 126, 120-137.

Starkey, P. & Cooper Jr, R. G. (1995). The development of subitizing in young children. *British Journal of Developmental Psychology*, 13, 399-420.

Svenson, O. & Sjöberg, K. (1978). Subitizing and counting processes in young children. *Scandinavian Journal of Psychology*, 19, 247-250.

Svenson, O. & Sjöberg, K. (1983). Speeds of subitizing and counting processes in different age groups. *The Journal of Genetic Psychology: Research and Theory on Human Development*, 142, 203-211.

Trick, L. M. & Pylyshyn, Z. W. (1993). What enumeration studies can show us about spatial attention: Evidence for limited capacity preattentive processing. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 331-351.

Trick, L. M. & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review*, 101, 80-102.

Watson, D .G., Maylor, E. A., & Bruce, L.. A. M. (2007). The role of eye movements in subitizing and counting. *Journal of Experimental Psychology: Human Perception and Performance*, 33, 1389-1399.

(Received August 1, 2019; accepted October 21, 2019)