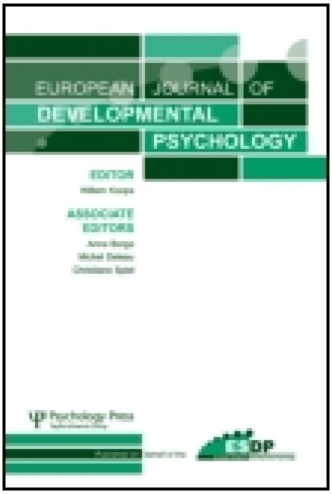

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Numerosity discrimination: Infants discriminate small from large numerosities

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Two experiments investigated numerosity discrimination in 7-month-old infants, comparing their performance on numbers within the range of subitizing (2 and 3 elements) with numbers marking the limit of this range, 4 elements, or lying outside this range (5 and 6 elements). The first experiment identified 3 as the upper limit of the small range of numbers by contrasting the discrimination tasks 3 vs. 4 with 4 vs. 5. The second one found, that infants can not only discriminate 2 from 4, discrepant from the finding of Xu (2003), but also 3 from 6 elements. It is discussed, that changing the continuous quantity of small numerosities will bias the infants towards element by element comparisons instead of comparing numerosities. Nevertheless, the study corroborates the finding from Xu (2003), that there are two systems of numerosity representation.

INTRODUCTION

A basic building-block of cognition is discrimination, which is a fundamental constituent of every cognitive process. Cognition is based on the perceptual systems, which allow for a range of sense modality specific discriminations, e.g., brightness, loudness or warmness. A major regularity of discrimination that is reliably found in various senses, various ages of one species and across species is the Weber–Fechner law. In order to perceive a difference between two stimuli, not their absolute difference but their relative difference is effective for noticing such a difference. There are qualities that are amodal, i.e., they can be discriminated in different sense modalities. Such a so-called primary quality is numerosity, which is a discrete quantity, because one can count, e.g., tones, light flashes, objects in the dark by touching them one after another. The difference between discrete and

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continuous quantities is their countability, which in language is reflected by count nouns and mass terms. It is relative easy to count the rain drops on my window, but it doesn't make sense to count the water, say in a lake. But even discrete quantities must extend into a certain space–time region in order to be perceived and discriminated one from another, so the difference between discrete and continuous quantities in perception is a matter of degree. Nevertheless, counting together with the concept of number is the base of arithmetic and mathematics that is valued as one of the major cultural achievements of mankind. Counting has a developmental course and it is of special interest to study its earliest precursor competence, which is to be seen in the discrimination of quantities.

In developmental psychology research on human preverbal infants has been done to identify precursor competences of the ability to count and other numerical abilities like using certain symbols such as number signs and applying them according to counting rules (e.g., Gelman & Gallistel, 1978). A certain problem can be seen in the fact that in the human case counting is a kind of discrimination by assigning each entity to be counted a unique sign, i.e., a number sign. Human preverbal infants do not discriminate discrete quantities in this symbolic manner, because a string of fixed ordered counting signs like the decimal numbers is not available to them and they cannot apply the performance rules of counting. But it has been found in several studies that they show sensitivity to differences in small numerosities (Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981; Treiber & Wilcox, 1984), even if the correlation of numerosity with continuous quantities such as size, area, or contrast is controlled (van Loosbroek & Smitsman, 1990). The precision in discriminating small numerosities contrasts with the imprecision in discriminating larger numerosities (Lipton & Spelke, 2003; Xu, 2003; Xu & Spelke, 2000). These findings correspond with probabilistic discrimination models related to the Weber–Fechner Law (van Oeffelen & Vos, 1982), which holds not only for continuous quantities like weight, length or contrast, because discrete quantities also occupy continuous space area and are perceived for a certain duration.

Moreover, the conclusion is premature that the greater precision in discriminating small numerosities up to four is indicative of counting. It would be a misapplication of the concept of counting, if infants are ascribed the ability to count, because counting is based on a generic symbolic number system that allows the generation of an infinite number of distinct signs and therefore counting is independent of the set size to be enumerated within the limits of finite human counting practice. Infants' ability to discriminate small numerosities should not be taken for counting, because this can be explained by a mechanism of percept formation that gives rise to the phenomenon of subitizing (Kaufman, Lord, Reese, & Volkmann, 1949), found mostly in adult humans utilizing reaction time (RT) as a dependent variable. As a function of numerosity, RT does not increase for the range of small numerosities up to three or four, in contrast to a significant increase after four. This discontinuity of the RT function is seen as evidence for at least two different processes of enumerating numerosities.

There is some disagreement concerning the representational basis of subitizing. Gallistel and Gelman (1992) described subitizing as a very fast kind of non-verbal counting. Trick and Pylyshyn (1994) interpreted subitizing as a by-product of processes of segmentation and binding underlying object formation in early vision. A preattentive capacity-limited mechanism, which they dubbed finger instantiation (FINST), is supposed to assign reference tokens in a pointer-variable manner in order to individuate features and to limit the computational costs associated with keeping track of a larger number of items. The optimal number appears to be four. A comparable model with largely similar implications is the object – file model of Kahneman and Treisman (1984). Both accounts of object formation out of a small number of object primitives have been generalized to the indexing hypothesis (Leslie, Xu, Tremoulet, & Scholl 1998): object primitives are individuated using a small set of indices that work like "mental pointers". Because dissociations between subitizing and counting have been found in patients, suffering from simultanagnosia (Dehaene & Cohen, 1994), small-numerosity discrimination seems to be based on a non-numerical mechanism. A non-numerical mechanism such as "indexing" is a plausible candidate for explaining the difference between subitizing and counting, which should already be functional in newborn infants, because infants can segment visual scenes, and individuate objects and sounds (Simon, 1997). This implies that in infancy the discrimination of small and large numerosities depends on different mechanisms, an object-tracking system ("indexing") and a numerosity approximation system that works according to the Weber–Fechner Law (Feigenson, Dehaene, & Spelke, 2004).

In a recent study, Xu (2003) found that infants could not discriminate between two and four objects. This is surprising, because infants do not generally fail to discriminate between small numbers, as is the case with two and three (Starkey & Cooper, 1980). This is at odds with conclusions that can be drawn from an object-tracking mechanism based on assigning a fixed number of mental pointers. It can be assumed that this divergence from some other numerosity discrimination studies carried out with infants was caused by the variation of the continuous quantity of the elements. In Xu's Experiment 2, on average, two dots occupied a comparable space to four dots, but compared to Experiment 1 in the same study, the individual elements were twice as large. As Xu herself states, this may have biased infants to compare single objects rather than numerosities. We hypothesize that infants can discriminate a small numerosity from the within-subitizing range from a numerosity marking the subitizing limit or lying outside this limit, if elements are made up of a constant continuous quantity and occupy a comparable display area. We reason that if the visual angle of a single element and of the whole display respectively is to a large extent made smaller than the visual angle Xu utilized, differences between the continuous quantities of the numerosities are of less importance. The reasoning is that the major accomplishment of an index-limited object formation system is the simultaneous individuation of features grouped in one whole. If the visual angle is so small that infants can easily perceive the whole group of elements, the unit of comparison will not be a single object, but the discrete quantity of the group of elements. Therefore infants should be able to discriminate two from four, and three from six elements.

EXPERIMENT 1

In accordance with Xu's assumptions, we hypothesized that the Weber–Fechner Law of discrimination would not be valid within the range of small numerosities in contrast to numerosities outside this range. This law of discrimination is based on the assumption that the relative difference of two stimuli necessary to notice a change in one stimulus, called just notable difference (*jnd*), is constant over the dimension of discriminanda. By adding this *jnd* to the value S of the discriminandum in question and by dividing the sum $S + jnd$ by S, a constant ratio is obtained, the Weber fraction. Fechner's law is an extension of this regularity by an logarithmic function: $S' = \mathrm{c} \log S$, where S' is the magnitude of the sensation, S is the logarithm of the physical magnitude of the stimulus, and k is a constant that takes into account the specific Weber fraction for a given dimension of discriminanda. An equivalent formulation is that the threshold of discrimination between two stimuli increases linearly with stimulus magnitude.

If there are at least two different mechanisms in perceiving small and large numbers, an indexing mechanism for a numerosity range up to four and a number approximation system for numbers greater than four, then the relative difference between small numbers is not computed for the discrimination of small numbers, i.e., the Weber fraction is not valid in the case of small numbers. This would provide extra evidence that small-number discrimination is based on a different mechanism to the discrimination of large numbers. A small set of objects is individuated object by object, because the indexing mechanism assigns each object a pointer. A larger set of objects is individuated as a whole by using information like inter-object distance, area occupied by objects and contrast. Infants should discriminate small numerosities, e.g., 2 vs. 3, but should not discriminate 4 vs. 6 elements in spite of the same Weber fraction. For the indexing mechanism there are not enough indices to individuate the numerosity 6, and the Weber fraction of 33% is not enough for the number approximation system to arrive at a reliable discrimination (Xu & Spelke, 2000). Indeed, Starkey and Cooper (1980) found that infants with an average age of 4 months discriminated 2 vs. 3 dots, but not 4 vs. 6 dots, but the generalizability of this finding is limited, because they only used linear arrays. Therefore, in the following experiment an infant-controlled habituation technique was utilized, comparable to the procedure used by Starkey and Cooper (1980) with non-linear arrays.

Method

General remarks concerning participants. In general, each infant–caregiver dyad took part in only one experiment dealing with numerosity discrimination and was not followed up thereafter. The parents were contacted by visiting baby groups or by advertisements in local newspapers. They were informed that the infants would just have to look at different stimuli, that the infants would always stay with their mothers by sitting on their laps and that the whole situation would be arranged in order to allow both caregiver and infant a comfortable stay. Additionally, they were told that no medical examination, no testing of general psychological functions would be done and that consequently no kind of diagnosis concerning any ability of the infant would be given. All caregivers were told that at any time during the lab visit they could feel free to end participation as a result of any signs of distress on the part of the infant, the caregiver or both. Finally, they were told that participation would not be paid. At the beginning of the experiment, all caregivers had to give their written consent to their infants being filmed, state that they had been informed about the study and that they understood that their infants' data were only to be used for scientific purposes. After the experiment a Polaroid picture was taken of the infant and the caregiver, and they were given a little booklet with some information about infancy research and addresses that could be consulted concerning questions of infant health and care.

Because there was no hypothesis formulated concerning the effect of sociodemographic status of the caregivers on numerosity discrimination, no such information was collected. But most of the addresses indicating the parents living places, the baby groups they joined and the impressions from interacting with them allow the inference that most of them were typical middle-class members of society.

For each of the three experiments a minimum sample size of 32 infants was approached, because there were four habituation groups and due to test power considerations it was thought necessary to have at least eight infants in each group to test for order effects of test stimulus presentations. In each experiment infants were randomly assigned to each habituation and test order group.

Participants. A total of 43 healthy, full-term infants participated in the experiment, who, according to their caregivers, had no problems with vision or hearing. Of these, 10 infants had to be excluded from the sample because five did not habituate and five were fussing. The 33 infants ranged in age from 175 to 223 days (mean 221.9 days; *SD* 21.2 days); 14 infants were male and 19 infants were female.

Materials. The stimuli were presented on slides by projecting them centred on a white back-projection screen (92.4 × 71 cm) that was mounted on the back-drop of a small puppet stage (110 × 50 × 65 cm mounted on a scaffold 91 cm above the floor). The projected area of the slides measured 23 × 35 cm and contained a 6 × 6 virtual matrix centred within it, of which 2, 3, 4 or 6 cells were randomly chosen. The only restriction in the case of three dots was that half of them were linearly ordered and the other half were triangularly ordered. A magenta-red dot with a diameter of 8 mm could be placed in every cell. The minimal distance between dots was 2 cm and the maximal distance was 10 cm. The distance of the infant's head from the projected display was 80 cm, and thus the visual angle for one dot was 0.7 degrees, and the minimal visual angle of the whole display ranged between 2.7 and 8.6 degrees. Luminance at the infant's head was always 600 lx, with a dot illuminance of 29 cd m^{-2} and screen illuminance of 105 cd m^{-2} with a contrast of 56.7%. For every infant, 24 slides were produced, 20 with numerosity n and four with numerosity $n+1$ or vice versa (20 with $n+1$ and four with n). Every configuration and every series was presented only once.

Design and procedure. In a sound-protected laboratory the infants sat on the laps of their mothers, who were instructed to close their eyes, in front of the stage. A micro-camera was mounted 2 cm below the floor of the stage. The lens was directed towards the infant's head through a small peep hole in a grey velour cloth wrapped around the scaffold and the stage. The infant's head could be seen on a video screen behind the stage, where observer 1 projected the slides by operating a presentation program on a laptop connected to a projector. Observer 1 was connected via earphones to observer 2 in another laboratory, who could see and hear the infant and see the stimuli on separate video screens and recorded the audiovisual signals. Observer 2 registered online the looking time of the infant by pressing a mouse button if the infant was looking at the target and by releasing the button if the infant was not looking at the target. The respective on-target and off-target looking times of the infant were registered. According to predetermined on-target and off-target looking times, observer 2 initiated and consecutively stopped separate trials by giving corresponding commands to observer 1. A trial was stopped if the infant looked for 0.5 s or more at the stimuli and looked away from the display for at least 2 s, or if the infant did not look at the stimuli for 30 s. If the infant was off-target for four trials the procedure was stopped. The program computed the criterion for habituation by averaging the looking time for the first three trials, which were compared with the moving average of three consecutive trials, starting with trial 4. The criterion for habituation was reached if the moving average was 50% or less of the average looking time for the first three trials. The maximum number of habituation trials was 16. There were eight test trials and each numerosity (2 or 3 in one group, 4 or 6 in the other group) served equally often as habituation and test stimulus. The test stimulus is a new stimulus, i.e., a stimulus that differs in one aspect from the stimuli presented in the habituation phase. The only critical difference was difference in numerosity. Thus, the two numerosity groups were split into four habituation groups, and the order of presentation of the new or the familiar numerosity in the test phase was counterbalanced, resulting in eight test groups. There were almost equal numbers of female and male infants in every numerosity group.

Results

The mean number of trials taken to reach the habituation criterion was 8.4 (*SD* 2.6) in the total group, 9.0 (*SD* 2.8) in the 2 vs. 3 group ($n = 17$) and 7.7 (*SD* 2.3) in the 4 vs. 6 group ($n = 16$). Data for the measure "looking time" were analysed using a $2 \times 2 \times 2 \times 2$ analysis of variance (ANOVA) (mixed model) with the between-subject factors "discrimination" (2 vs. 3 vs. 4 vs. 6), "order of presentation" (familiar – new vs. new – familiar) and "sex", and within-subject factor "novelty" (familiar numerosity vs. new numerosity). Looking times were sums over four test trials, new or familiar numerosities, respectively. The only significant effects at the level of $p = .05$ were "novelty", Wilks $\Lambda = .80$; $F(1, 25) = 6.25$, and the interaction "discrimination $\times$ novelty", Wilks $\Lambda = 86$; $F(1, 25) = 4.21$. The novelty effect differed in the two discrimination conditions (cf. Figure 1), as shown by separate contrasts. In the condition 2 vs. 3, the infants looked at the new numerosities significantly longer [mean difference "familiar – new" -4660 ms, *SD* 6105.86 ms, $F(1, 31) = 10.56$] in contrast to the condition 4 vs. 6 [mean difference "familiar – new" -777 ms, *SD* 5700.64 ms, $F(1, 31) = 0.28$]. Of the 33 infants, 20 (60.6%) looked for longer at the new numerosities.

Discussion

Infants discriminated 2 from 3 and 3 from 2 dots, but not 4 from 6 and 6 from 4 dots. This was indicated by the novelty effect. In the 2 vs. 3 group, half of the infants looked longer at the novel stimulus 2 dots in comparison

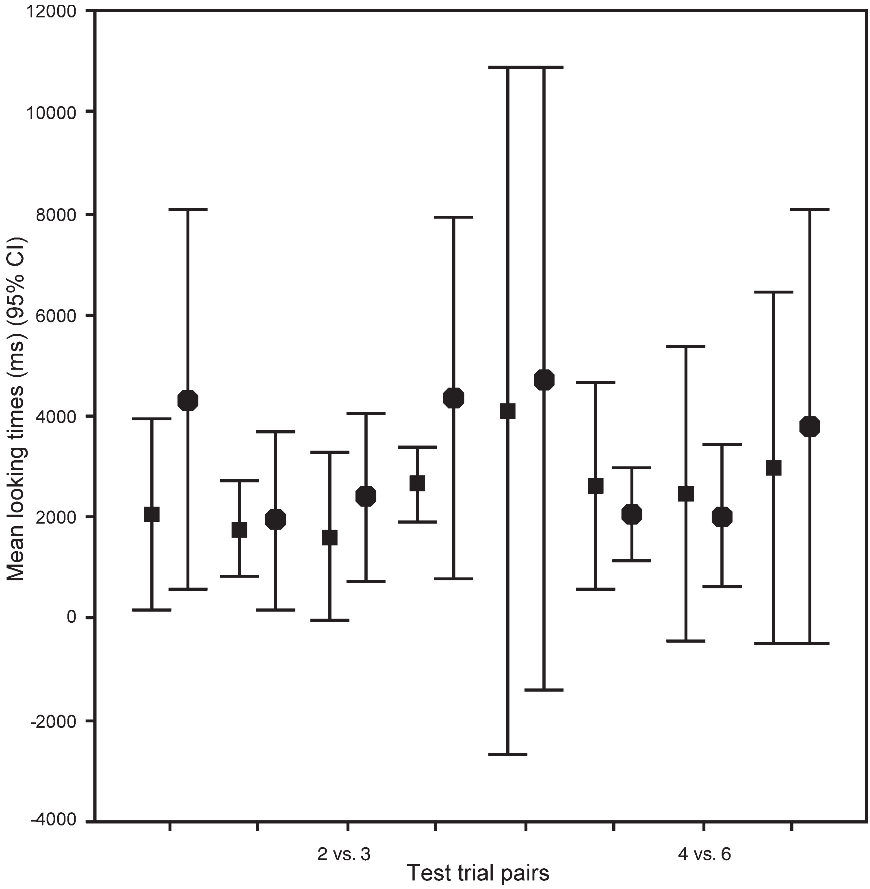

Figure 1. Numerosity discrimination: 2 vs. 3 and 4 vs. 6 dots.

to 3 dots they saw in the habituation phase and the other half looked longer at the novel stimulus 3 dots in comparison to the familiar 2 dots. Therefore, it can be concluded that the infants discriminated 2 from 3 dots, but not 4 from 6 dots due to the lack of a novelty effect in the latter condition. Infant sensitivity to differences in numerosity is restricted to 2 vs. 3 dots, corroborating the results of Starkey and Cooper (1980), who utilized only linear dot arrays; 4 vs. 6 dots were not discriminated, despite the fact that they have the same Weber ratio. This corresponds with the findings of Xu and Spelke (2000), who found that, on average, 6-month-old infants can discriminate 8 from 16 dots, but not 8 from 12 dots. Thus, the Weber–Fechner Law does not hold for small numerosities.

EXPERIMENT 2

In adults the upper limit for enumerating and discriminating small numerosities very quickly and nearly without error in the visual domain is 3 or 4 (Trick & Pylyshyn, 1994). Because infants can discriminate 2 from 3 objects, but not 4 from 6, the question is whether they can recognize 3 objects. Therefore, analogous to Experiment 1, two discrimination conditions were used: 3 vs. 4 dots and 4 vs. 5 dots. Treiber and Wilcox (1984) demonstrated that infants with an average age of 4 months discriminated 4 vs. 5 dots arranged randomly, but they utilized an experimenter-controlled fixed-presentation-time technique and not an infant-controlled habituation–dishabituation paradigm. They aggregated looking times of different duration and it cannot be ruled out that using cumulated looking times leads to overestimation of discrimination. Moreover, if the infants can discriminate 3 vs. 4, additional evidence should be available to reliably identify the upper limit of small numerosity discrimination in infants.

Method

Participants. A total of 49 healthy, full-term infants participated in the experiment, who, according to their caregivers, had no problems with vision or hearing. Of these, 9 infants had to be excluded from the sample because four did not habituate and five were fussing. The 40 infants ranged in age from 180 to 219 days (mean 211.4 days, *SD* 20.72 days); 21 infants were male and 19 infants were female. The parents were contacted by visiting baby groups or by advertisements in local newspapers.

Materials, procedure and design. Numerosity stimuli were constructed as described for Experiment 1 (3, 4 and 5 dots). The procedure and design were also as described for Experiment 1. Controlling for habituation stimulus numerosity and test order within the two numerosity groups yielded four habituation groups, with two test order groups for each of these.

Results

The mean number of trials taken to reach the habituation criterion was 8.2 (*SD* 2.6) in the total group, 8.3 (*SD* 2.7) in the 3 vs. 4 group ($n = 20$) and 8.2 (*SD* 2.5) in the 4 vs. 5 group ($n = 20$). Data for the measure "looking time" were analysed using a $2 \times 2 \times 4 \times 2$ ANOVA (mixed model) with the between-subject factors discrimination (3 vs. 4 vs. 4 vs. 5), order of presentation (familiar–new vs. new–familiar) and within-subject factors test trial pairs (first, second, third and fourth) and novelty (familiar numerosity vs. new numerosity). The only significant effects at the level of $p = .05$ were novelty, Wilks $\Lambda = .80$; $F(1, 36) = 8.93$, and the interaction discrimination × novelty, Wilks $\Lambda = .86$; $F(1, 36) = 5.82$ (cf. Figure 2). Separate analysis of the two discrimination groups showed that within the group 3 vs. 4 only the novelty effect was significant, $F(1, 18) = 12.31$, which was not significant in the group 4 vs. 5, $F(1, 18) = 0.20$. Of the 40 infants, 31 (77.5%) looked for longer at the new numerosities.

Discussion

The findings indicate that infants can recognize a numerosity of cardinal value 3, because, besides discriminating 2 from 3 elements, they can

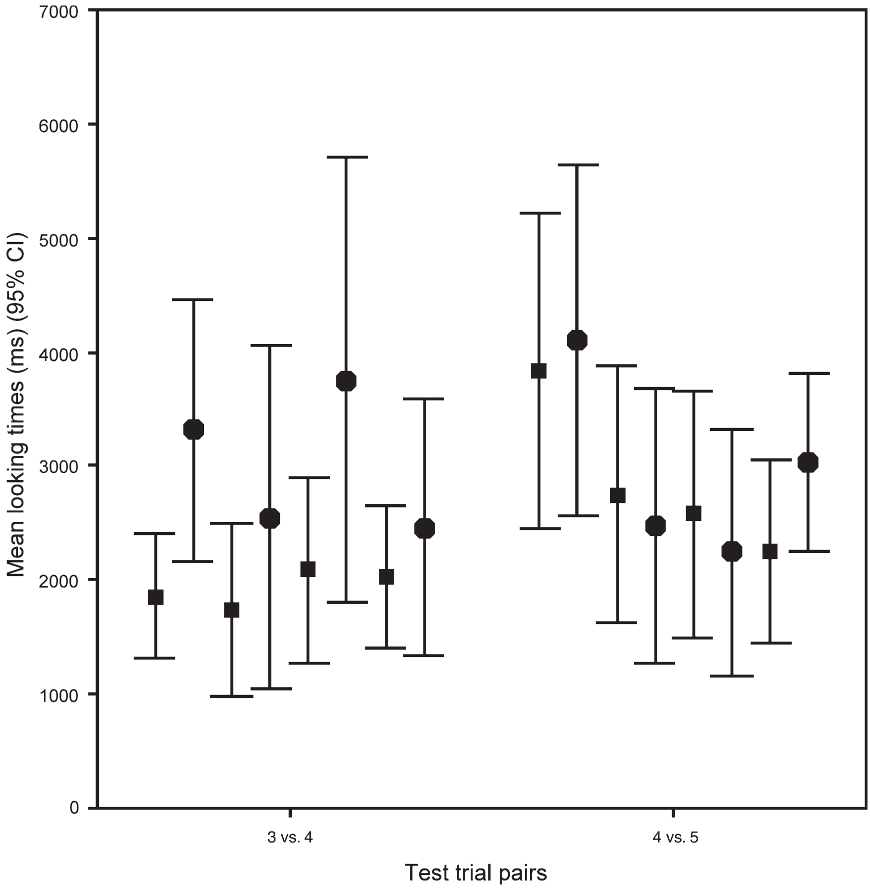

Figure 2. Numerosity discrimination: 3 vs. 4 and 4 vs. 5 dots.

discriminate 3 from 4 objects, but not 4 from 5, in contrast to results found by Treiber and Wilcox (1984). Contrasting the infant data with data from experiments with adult persons, the upper limit for discriminating small numerosities seems to be 3, sometimes 4, a finding that is in accordance with data from subitizing studies with adults (Trick & Pylyshyn, 1994).

EXPERIMENT 3

It was hypothesized that infants can discriminate numerosities from the within-subitizing range from numerosities at the subitizing limit and outside this range: (1) if their ratio is 1:2; (2) if the elements are of equal continuous quantity; and (3) if the visual angle of the stimulus display is as small as possible. The discriminant pairs chosen for study were 2 vs. 4 and 3 vs. 6. It was assumed that presenting sets made up of qualitatively identical elements in series would make the numerosity property of small sets more salient than the individual object, as was perhaps the case with varying the continuous quantity of single elements (Xu, 2003).

Method

Participants. A total of 45 healthy, full-term infants participated in the experiment. Of these, 5 infants had to be excluded from the sample because one did not habituate and four were fussing. The 40 infants ranged in age from 187 to 229 days (mean 210.4 days, *SD* 16.51 days); 22 infants were male and 18 infants were female. The parents were contacted by visiting baby groups or by advertisements in local newspapers.

Materials, procedure and design. Numerosity stimuli were constructed as described for Experiment 1 (2, 3, 4 and 6 dots). The procedure and design were also as described for Experiment 1. Controlling for habituation stimulus numerosity and test order within the two numerosity groups yielded four habituation groups, with two test order groups for each of these.

Results

The mean number of trials taken to reach the habituation criterion was 7.9 (*SD* 2.1) ($n = 20$) in the 2 vs. 4 group and 8.3 (*SD* 2.4) ($n = 20$) in the 3 vs. 6 group. Data for looking time were analysed using ANOVA over factors analogous to Experiment 1. The only significant effect at the level of $p = .05$ was novelty, Wilks $\Lambda = .68$; $F(1, 36) = 17.35$. No other effects were statistically significant ($p > .1$). The novelty effect in the two discrimination conditions (cf. Figure 3) was also significant [2 vs. 4: $F(1, 18) = 15.15$; 3 vs. 6:

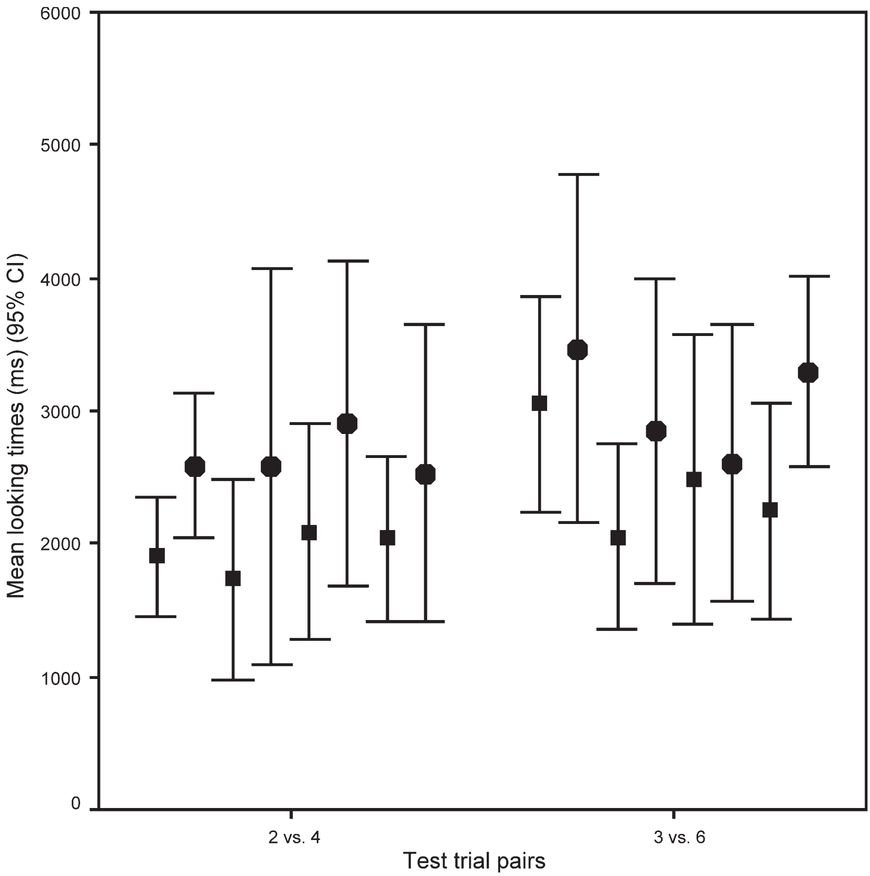

Figure 3. Numerosity discrimination: 2 vs. 4 and 3 vs. 6 dots.

$F(1, 18) = 5.48$]. Of 40 infants, 33 (77.5%) looked for longer at the new numerosities. Therefore, there are certain limitations to the generality of the conclusion of Xu (2003) that infants fail to discriminate between small numerosities, at least having a ratio of 1:2. The same holds for recent findings of Xu, Spelke and Goddard (2005) who found that 6-month-old infants succeeded in discriminating 16 vs. 32, but not 1 vs. 2 dots.

GENERAL DISCUSSION

The empirical findings indicate that, in accordance with several studies, infants discriminate small and larger numerosities in different ways. Within the subitizing range they can discriminate at a ratio of 3:2 and even at a smaller ratio of 4:3, but not for numerosities with the same ratio but with larger absolute values, such as 4 vs. 6 or 8 vs. 12 (Xu & Spelke, 2000). Because they cannot discriminate 4 from 5 elements, they have a comparable upper limit for the subitizing range (3 elements) as was found with adults. In contrast to the findings of Xu (2003), they can also discriminate within-subitizing range numerosities from outside-subitizing range numerosities, such as 2 vs. 4 and 3 vs. 6, with a ratio of 1:2. Regardless of the causes of discrepancy, our finding limits the general conclusion that infants fail to discriminate small numerosities with a ratio of 2:1, but they support the other general conclusion that there are two different mechanisms underlying the discrimination of small and larger numerosities.

What are the possible causes of discrepancy? One possible cause may be that in our study the infants were approximately 1 month older than in Xu's study, and there is evidence that the precision of numerosity discrimination develops with age in infancy (Lipton & Spelke, 2003). A more important cause is to be found in the differences of our objects and in the presentation of our numerosity displays. First, we did not control for the continuous quantity of the individual dots, because we wanted to control for differences in object appearance by holding the qualitative identity of the dots constant. We intended to make the appearance of the numerosity more salient than that of the objects, because in the case of small numerosities individual objects differing in continuous quantity may make the object dimensions more salient. Therefore, according to Xu (2003), the object-tracking system may win out: "when presented with small numbers of items, infants keep track of individual objects and fail to register the cardinal value of the set" (p. B24). The only difference between the dots were in their spatial location, which varied from presentation to presentation, thus making it more difficult to compare sets object by object. Thus, the indexing mechanism can make use of spatial locations only in the case of small numerosities, and larger numerosities such as 4 and 6 may trigger the number comparison system. If numerosity 3 is assigned with three indices, this would be enough to discriminate it from a numerosity twice as large, which cannot be indexed by the object-tracking mechanism. Second, we presented the display of numerosities at a much smaller angle of vision than Xu (2003) did. This was done to make, together with the qualitative identity of the elements, the numerosity aspect more salient and to reduce the number of eye movements needed to scan the display.

Nevertheless, it cannot be ruled out that the continuous amount of dots, the continuous quantity of area occupied and the total contrast of the set was used as information to discriminate the sets. This imposes a certain limitation on the conclusion that the findings are indicative of enumeration produced by a discrete quantification mechanism. Some studies found evidence that infants base their discriminations on continuous variables rather than number. Clearfield and Mix (1999) habituated sixteen 6- to 8-month-old infants to displays of either two or three black squares on a page. They were then tested with alternating displays of either a familiar number of squares with a novel contour length or a novel number of squares with a familiar contour length. Infants dishabituated to the display that changed in contour length, but not to the display in number. In the case of dynamic displays, Clearfield (2004) showed that infants' looking at event sequences, the jumping of puppets two or three times, is based on amount of motion, not on enumeration. Mix, Huttenlocher and Levine (2002) review the literature on multiple cues for quantification in infancy and conclude that there is no clear-cut evidence of number being one of them. In our view, this conclusion should be differentiated in relation to the set sizes studied. The assumption that counting is used to discriminate large numerosities, i.e., numerosities lying outside the subitizing range, is not correct as has been shown by number discrimination studies utilizing reaction-time methods, e.g., Trick and Pylyshyn (1994). In this case the occupancy model of perceived numerosity is better suited for explanation by assuming that the area of the stimulus plane occupied collectively by all dots provides a better basis for judging relative numerosity (Allik & Tuulmets, 1991). Large numerosity discrimination is based on continuous quantity and can be described by the Weber–Fechner law, but is there clear-cut evidence that number cannot be utilized if small numerosities are to be discriminated? In our view there is no clear-cut evidence that infants only use continuous quantity in discriminating small numerosities, i.e., numerosities lying within the subitizing range. We found that the Weber–Fechner law was not valid in case of small numerosities, which allows the conclusion that small numerosities are discriminated differently from large numerosities. Infants perceive not only continuous quantity, because infants can individuate single objects and discriminate one from an other even if the objects look alike, i.e., are qualitatively identical (Xu & Carey, 1996).

Therefore, according to the indexing hypothesis it is not plausible that the number-estimation mechanism is at work in the case of small numerosities up to 3 (Xu, 2003). Outside this numerosity range, a number-estimation system starts working and the numerosity is not individuated element by element, but by subgrouping and/or computing additional numerosity-related continuous quantities, e.g., average density. Small sets of objects can be compared object by object, and proficient counters immediately see the number of the set if asked to judge the numerosity of both sets. The ease of answering which set has more objects than the other in the case of small sets depends on understanding the relevant dimension of judgement and on knowing the numbers. However, infants do not know numbers and do not understand which dimension of the small set is relevant for comparison. The object-tracking system is not a number system and it is reasonable to assume that infants focus on the separate objects in the case of small numerosities, especially if the objects differ in size. The numerosity dimension of sets of objects differing in appearance becomes more salient only in the case of larger numerosities, thus triggering the number estimation system. Qualitatively identical objects, i.e., objects with equal outlook and only differing by spatial location, can make the numerosity dimension more salient if presented close together. Therefore, the findings do not contradict the conclusion of Xu (2003) that there are two mechanisms for enumeration, but it seems to be premature to conclude that infants cannot discriminate within-subitizing range numerosities from outside-subitizing range numerosities.

One implication of this conclusion is that the discrimination of small numerosities is a case of object perception. The discrimination of objects implies at least two objects, which are discrete and therefore countable. Visual perception is based on segmenting the environment into stable units, i.e., units that can be tracked over time. The formation of units is based on subunits, i.e., features like lines, line crossings, edges, etc. The indexing hypothesis postulates indexes that are part of these segmentation and binding processes that are central in object formation processes in vision. It is an open question, if the indexing hypothesis is also valid in the other sense modalities. Therefore, discriminating small numerosities works like discriminating objects, because in every object discrimination discrete quantification is inseparably implied. Adult persons see that there are, e.g., three objects, because they know numbers and are normally experienced in quantifying sets by symbolic counting in contrast to infants. But infants individuate objects and their object formation and tracking mechanisms allow them to discriminate small numerosities. Because they are sensitive to object differences, they are also sensitive to discrete quantities. Therefore, it is not necessary to ascribe numerical competences to infants. Their ability to discriminate large numerosities also makes this unnecessary. It is more parsimonious to explain this achievement by their sensitivity to continuous quantities like the area occupied by the objects and/or the sum total of the contrast differences between the discriminanda sets. Future studies have to show whether it is justified to assume a special number sense or an innate special numerical capacity (e.g., Dehaene, 1997). Numerosity is a stimulus dimension nearly all species take into behavioural account, but this has to do with the intrinsic quantitative nature of the senses, which have to build up and utilize a cognitive map of the space – time structure of the environment (Davies & Pérusse, 1988). From a developmental point of view, counting is a symbolic quantification achievement like measuring that has necessary perceptual quantificational conditions, which are not sufficient to explain the arithmetic abilities of humans. The social practice of quantifying by using symbols and conceptual schemes like the ones of arithmetic and geometry taught in schools is a major condition of becoming a proficient number user.

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