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The Development of Area Discrimination and Its Implications for Number Representation in Infancy

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Abstract

This paper investigates the ability of infants to attend to continuous stimulus variables and how this capacity relates to the representation of number. We examined the change in area needed by 6-month-old infants to detect a difference in the size of a single element (Elmo face). Infants successfully discriminated a 1:4, 1:3, and 1:2 change in the area of the Elmo face but failed to discriminate a 2:3 change. In addition the novelty preference was linearly related to the ratio difference between the novel and familiar area. Results suggest that Weber's Law holds for area discriminations in infancy and also reveal that at 6-months of age infants are equally sensitive to number, time and area.

Introduction

Since Piaget's early studies of the development of conservation of quantity there has been great interest in the development of quantitative capacities (Piaget, Inhelder, & Szeminska, 1960). Recently a great deal of controversy has surrounded the issue of the relationship between the ability to represent number vs. continuous properties of a set in infancy. One strong view contends that successes on numerical discrimination tasks in infancy are best accounted for by a sensitivity to variation in continuous variables instead of number (e.g., Clearfield and Mix, 1999, 2001; Mix, Huttenlocher, & Levine, 2002; Newcombe, 2002).

While a handful of studies from the early 1980s suggested that infants could discriminate small sets such as 2 versus 3 based on number (e.g., Antell & Keating, 1983; Starkey, Spelke, & Gelman, 1983; Strauss & Curtis, 1981); those results were subsequently challenged by findings that suggested that infants do not discriminate number but instead attend to continuous variables, such as contour length and area (e.g., Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002). For example, Clearfield and Mix (1999) habituated 6-month-old infants to arrays of 2 or 3 squares with a constant total contour length. The infants were then tested with arrays that were familiar in number and novel in total contour length (and cumulative area), and arrays that were novel in number and familiar in contour length. Infants looked longer at the arrays that contained the novel contour length/familiar number compared to the arrays with a novel number/familiar contour length and only dishabituated to the change in contour length. Feigenson, Carey, and Spelke (2002) obtained similar findings with changes in cumulative surface area rather than contour length. Such studies suggest that infants may preferentially attend to continuous variables over number and have led some researchers to question whether infants make numerical judgments based exclusively on these variables (e.g., Mix, Huttenlocher, & Levine, 2002; Newcombe, 2002).

In contrast, other studies that have carefully controlled continuous variables have found that infants can in fact discriminate large numerosities (i.e., sets larger than 3; Brannon, 2002; Lipton & Spelke, 2003; Wood & Spelke, 2005; Xu, 2003; Xu & Spelke, 2000; Xu, Spelke, &

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Goddard, 2005). For example, when element size, cumulative surface area, and density were eliminated as cues, 6-month-old infants differentiate displays of 8 and 16 elements (Xu & Spelke, 2000; but see critique by Mix, Huttenlocher, & Levine, 2002). Generally these studies demonstrate that discrimination of large numerosities obeys Weber's Law; that is, the discriminability of sets is dependent upon their ratio and not their absolute difference such that at 6-months of age infants successfully discriminate values that differ by a 1:2 ratio (e.g., 4 vs. 8; 8 vs. 16; 16 vs. 32) but fail to discriminate when tested with values that differ by a 2:3 ratio (e.g., 4 vs. 6; 8 vs. 12; 16 vs. 24).

In addition a recent study by Brannon Abbott and Lutz (2004) demonstrated that although 6-month-old infants were able to discriminate a two-fold change in number when habituated to stimuli that were constant in number but varied 5-fold in area infants at the same age who were habituated to stimuli that varied 5-fold in number but were constant in area failed to detect a two-fold change in cumulative area. Those results suggest that infants may be more sensitive to the numerical attribute of discrete arrays than to summary statistics, such as cumulative area, for discrete arrays.

An important foundation for understanding the degree to which infants can attend to the cumulative surface area of a set of discrete entities is to understand infants' capacities for discriminating the area of single entities. However, only a few studies have examined the ability of infants to represent area independent of number. In one such study, Gao, Levine, and Huttenlocher (1999) used both the visual habituation paradigm and the violation of expectancy paradigm and demonstrated that 6-month old infants differentiate containers that are 1/4 full from those that are 3/4 full of red liquid. Thus by 6 months of age infants discriminate a 3 fold change in liquid inside a standard sized container. Similarly, 6-month old infants were shown to detect a 2-fold change in the size of a wooden dowel but only when a standard sized dowel was available as a basis for comparison (Huttenlocher, Duffy, & Levine, 2002). Importantly, although the studies reviewed above suggest that infants can discriminate continuous properties of single entities (nonsolid or solid), no study has yet to examine the precision with which infants can do this. Here we systematically investigate the psychophysics of area discrimination in infancy using the visual habituation paradigm by varying the ratio difference between the novel and familiar areas to determine the minimum ratio needed to distinguish between single entities.

Method

Participants

Participants were 32 healthy full-term 6-month-old infants (mean age = 5 months 29 days, range: 5 months 14 days-6 months 16 days). Fifteen of the infants were female. Data from an additional 9 infants were discarded because of fussiness resulting in failure to complete at least 4 test trials.

Design

Infants were habituated to stimuli with a single small *or* large Elmo face and then tested with a single small *and* large Elmo face. The ratio of the area of the small and large faces varied by a 1:4, 1:3, 1:2, or 2:3 ratio, and each infant was tested with only one ratio change. There were 8 infants in each condition. Half of the infants within each ratio condition were randomly assigned to the Small Area condition and half to the Large Area condition.

Stimuli

Stimuli were created with Canvas software and displayed in the center of a computer monitor (27 x 34 cm^2). Within each ratio condition, the area of the small Elmo face was held constant at 21.8 cm^2 (see Figure 1 for stimuli). The area of the large Elmo face was held constant at 87.2 cm^2 in the 1:4 condition, 65.4 cm^2 in the 1:3 condition, 43.6 cm^2 in the 1:2 condition, and 32.7 cm^2 in the 2:3 condition. Area was defined as the area of the smallest ellipse that encompassed the entire face. Although no standard was explicitly provided (Huttenlocher, Duffy, & Levine, 2002) the boundaries of the computer monitor likely served as a standard.

Apparatus

Infants were seated in a high-chair (or on a parent's lap) 60 cm from a computer monitor resting on a stage surrounded by blue fabric. Parents were seated next to their infants and instructed to keep their eyes closed and to refrain from talking to, touching, or otherwise interacting with their infant for the duration of the experiment. If an infant became fussy, the experimenter initiated a short break and then resumed the experiment. For an infant to remain in the final sample, the break must have been less than 1 minute in duration and could not occur between a pair of test trials.

A microcamera monitoring the infant's face and a feed directly from the stimulus presentation computer were multiplexed onto a TV monitor and VCR. One or two experienced experimenters blind to the experimental condition recorded the infants' looking behavior while viewing the live video with the display occluded. Looking behavior was recorded by holding a button down when the infant was looking at the computer monitor and letting go when the infant looked away. The button input was fed into a Visual Basic program, which automatically advanced the stimulus and automatically moved onto the test phase when the criterion was met. The Visual Basic program recorded infants as looking or not looking for each 100 ms interval and calculated inter-observer reliability. Reliability was conservatively computed based on agreement or disagreement between two observers, both blind to the experimental condition, at each 100 ms interval. Two observers were present for 29 out of the 32 participants and reliability was on average 93%.

Procedure

Informed consent was obtained from a parent of each participant before testing. The experimenter initiated trials when the infant looked in the direction of the computer monitor. Each trial continued until the infant looked for a minimum of .5 s and ended after the infant looked for a total of 60 s or looked away for a continuous 2 s. The habituation stimuli were presented until the infant met the habituation criterion (a 50% reduction in looking time over three consecutive trials, relative to the first three trials that summed to at least 12 s) or until 16 trials were completed[1]. After habituation, the infants were tested with 6 test trials according to the same procedure and alternated between familiar and novel areas.

Results

Twenty-three out of the 32 infants met the habituation criterion[2]. A 4 X 2 mixed-factor analysis of variance (ANOVA) testing the between-subjects factors of ratio condition (1:4, 1:3, 1:2, and 2:3) and the within subjects-factor of habituation period (looking time to the first 3 habituation trials versus the last 3 habituation trials) revealed a main effect of habituation period ($F(1,28) = 66.8$, $p<.001$) and no interaction between habituation period and ratio condition. In other

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[1] There were 12 habituation trials in the 1:4 condition due to a programming error, however this did not appear to effect the results other than reducing the number of infants in this condition who habituated.

[2] Seven of 8 infants habituated in both the 2:3 and 1:2 Ratio Conditions, 6 out of 8 infants habituated in the 1:3 Ratio Condition, and only 3 of 8 infants met the formal habituation criterion in the 1:4 condition. Failure to meet the habituation criterion in the 1:4 condition was due to the fewer number of habituation trials. Average looking-times to the novel and familiar test trials looked similar for the 3 infants in the 1:4 Ratio Condition who met the formal habituation criterion and the 5 infants who did not.

words, infants looked longer at the first 3 habituation trials than the last 3 habituation trials in all conditions ($t(31)=4.94$, $p<.001$).

Figure 2 shows the mean looking time for the 3 novel test trials and the 3 familiar test trials in each ratio condition. A 4 X 2 X 2 mixed-factor ANOVA testing the between-subjects factors of ratio condition (1:4, 1:3, 1:2, and 2:3) and habituation condition (small or large area) and the within subjects-factor of test trial type (novel or familiar area) on infants' looking time yielded a main effect of test trial type ($F(1, 24) = 21.76$, $p < .01$), a main effect of ratio condition ($F(3, 24) = 33.68$, $p < .05$), and an interaction between test trial type and ratio condition ($F(3, 24) = 3.17$, $p < .05$). No other main effects or interactions were significant. The means and standard errors are also shown in Table 1 for all test trials and for the first test trials alone.

Further analyses revealed that infants required a 1:2 ratio change in area to exhibit a novelty effect. Infants looked longer at the novel area than the familiar area in the 1:4 Ratio Condition ($t(7) = 2.87$, $p < .05$), the 1:3 Ratio Condition ($t(7) = 6.42$, $p < .01$), and the 1:2 Ratio Condition ($t(7) = 2.35$, $p = .05$) but did not look significantly longer at the novel area in the 2:3 Ratio Condition ($t(7) = .10$, $p = .92$)[3]. Table 1 shows the means and standard errors for each condition both for the averages of 3 familiar and 3 novel test trials and for the first trial data. Furthermore, 6 out of 8 infants in the 1:4 Ratio Condition, 8 out of 8 in the 1:3 Ratio Condition, 6 out of 8 the 1:2 Ratio Condition, and 4 out of 8 in the 2:3 Ratio Condition showed a novelty preference.

As shown in Figure 3, the magnitude of the novelty preference (looking time to novel-looking time to familiar) increased with the ratio of the novel to familiar area. A linear regression on the difference scores for the 4 conditions revealed a slope significantly different from zero ($t(30) = 3.36$, $p < .05$).

Discussion

The main finding was that at 6-months of age infants were unable to detect a 2:3 ratio change in the size of a single element and required a 1:2 ratio change to show a novelty preference. A second important finding was that the magnitude of the looking time difference between the familiar and the novel area test trials was modulated by the degree to which the areas differed. Collectively these findings suggest that infants are sensitive to area and that area discriminations follow Weber's Law in infancy.

The 1:2 ratio required for area discriminations in our study is particularly interesting because it is the same ratio that is required by 6 -month-old infants to detect a change in the number of visual or auditory elements (Lipton and Spelke, 2003; Xu and Spelke, 2000). Similarly, Van Marle and Wynn (in press) recently showed that 6-month-old infants required a 2-fold change in the duration of a stimulus to detect a change. Thus at 6-months of age infants show the same sensitivity to changes in number, time, and area.

The mode control model, developed by Meck & Church (1983) to explain the Weber-law characteristic of numerical and temporal discriminations in rats, contends that a single mechanism is used to represent duration and number via noisy mental magnitudes. Under this information-processing model, a pacemaker is proposed to emit pulses at a constant rate and the pulses are accumulated and result in a continuous magnitude representation for time or number. The pulses enter the accumulator via a switch that can operate in three different modes. Two of the modes result in the timing of the cumulative duration of individual events (stop mode) or an entire sequence of events including the intervals between events (run mode). The

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[3] The t-tests reported in the text are 2-tailed. When one-tailed t-tests were used all ratio conditions show significant differences in looking time between novel and familiar ($p < .01$) except for the 2:3 ratio condition ($p > .05$).

third mode operates as a counter (event mode) because the switch is closed for a constant duration for each event regardless of its actual extent. The strong claim of this proposal is that there is a quantitative equivalence between a count and an amount of time such that the final representations are interchangeable. Meck and Church offered three sources of evidence for the idea that rats use a single representational currency for time and number. First, the psychophysical curves for number and time in a bisection task superimposed. Second, administering amphetamine resulted in an identical 10% leftward shift of the psychophysical curves for both time and number. Third, and most powerfully, a discrimination trained on two durations that were each composed of a single continuous event transferred to a numerical discrimination.

Recently, it has also been proposed that representations of space (Walsh, 2003), and more generally, representations of all quantities obeying Weber’s law (Cordes & Gelman, 2005; Gallistel & Gelman, 2000), are represented by the same nonverbal system via noisy magnitudes. It is important to note that these latter claims are not focused on the idea that a single mechanism must be used to form different types of magnitude representations but instead focus on the idea that the resulting representations have a common format and perhaps also a common neural substrate (Walsh, 2003).

Our results suggest that at 6-months of age infants show the same sensitivity in their discrimination of number, time and area. An interesting question then is whether precision in area discrimination increases with age as it does for number and time. Lipton and Spelke (2003; see also Wood and Spelke, 2005) demonstrated that although 6-month-old infants fail to discriminate numerosities that differ by a 2:3 ratio, 9-month-old infants succeed. Similarly, Brannon, Libertus, and Suanda (in preparation; Libertus et al., 2005) have recently shown that although 6-month-old infants require a 1:2 ratio difference to discriminate changes in duration, by 10-months infants successfully discriminate a 2:3 ratio. If area discrimination shows the same developmental trend as number and time discrimination this would be further evidence of a common representational code underlying number, area, and time discrimination.

Although we have interpreted our results as evidence that infants are representing the area of a 2-dimensional display there are a few caveats. First, our study does not explicitly test the argument by Huttenlocher, Duffy, & Levine (2002) that infants require a standard as a basis for comparison when making volumetric judgments. Our paradigm did not explicitly provide a standard for comparison however it is likely that the bright white computer monitor served as a standard. Second, infants may have relied on perimeter rather than area[4]. This possibility seems unlikely given that Elmo’s face was irregular and had jagged edges. Furthermore, area increases as the square of perimeter increases such that when perimeter is doubled area quadruples. Thus if infants did rely on perimeter they detected very fine differences in perimeter (e.g., in the 1:2 area condition there was only a 1:1.4 change in perimeter).

A final possibility is that rather than area per se, infants attended to the distance between the edge of the computer monitor and a point (e.g., an eye) in the original stimulus and detected the change in physical location of that point in the novel sized-stimulus relative to the computer monitor. This seems unlikely because changes in relative distances between the edge of the computer monitor and salient points in the Elmo face (e.g., eye and cheek) were much smaller than the area changes (e.g. for the 1:2 area condition the cheek moved relative to the computer monitor in a 1:1.13 ratio). Again this would imply substantially greater sensitivity to distances than area (or time or number).

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[4] Perimeter was difficult to calculate because of the very jagged edges to Elmo’s face however a crude measurement using Adobe illustrator determined that perimeter was approximately 17.9 cm for the smallest Elmo face.

In conclusion, parallels in sensitivity at 6 months of age between number, time, and area are compatible with the idea that a single representational currency underlies these dimensions, however, additional data are necessary to test that hypothesis. Meck and Church (1983) argued that there is a quantitative equivalence between a count and 200 ms and that magnitude representations formed by timing could be used in subsequent number discriminations and vice versa. Future research should test such predictions in infants and nonhuman animals for area, number, and time. Ultimately we will need to determine the mechanisms by which number, area, and time representations are established as well as how they are compared to provide a complete picture of the systems underlying these different analog magnitude representations. Furthermore, it would be important to test whether all ordinal continua (e.g., line length, brightness, volume, number, weight, duration) share a common representational code or whether there is a more privileged relationship between number, time, and area.

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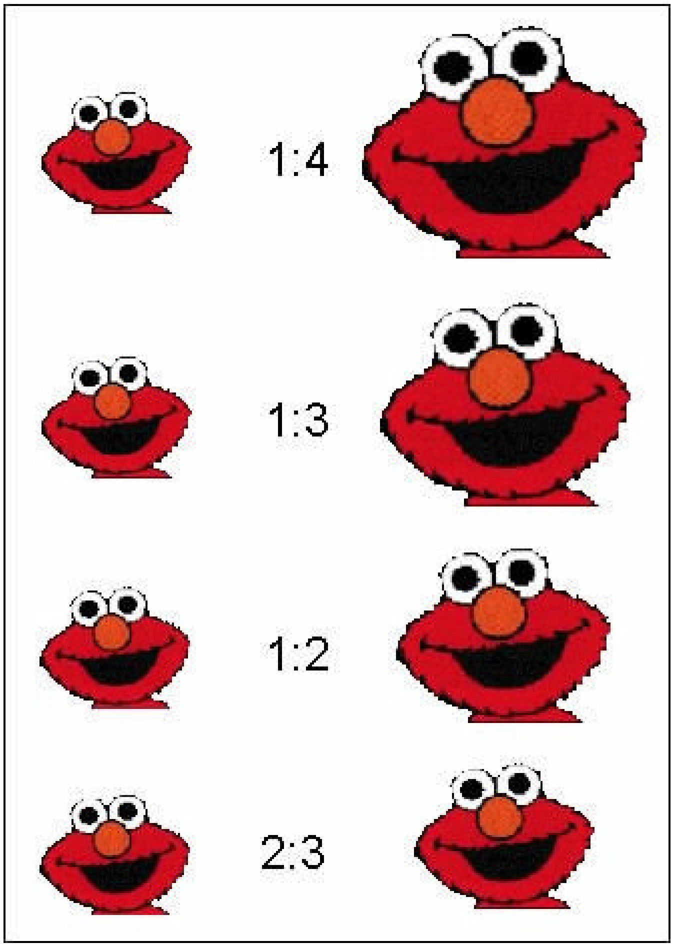

Figure 1.
Schematic representation of the ratios of the stimuli used in Experiment 1.

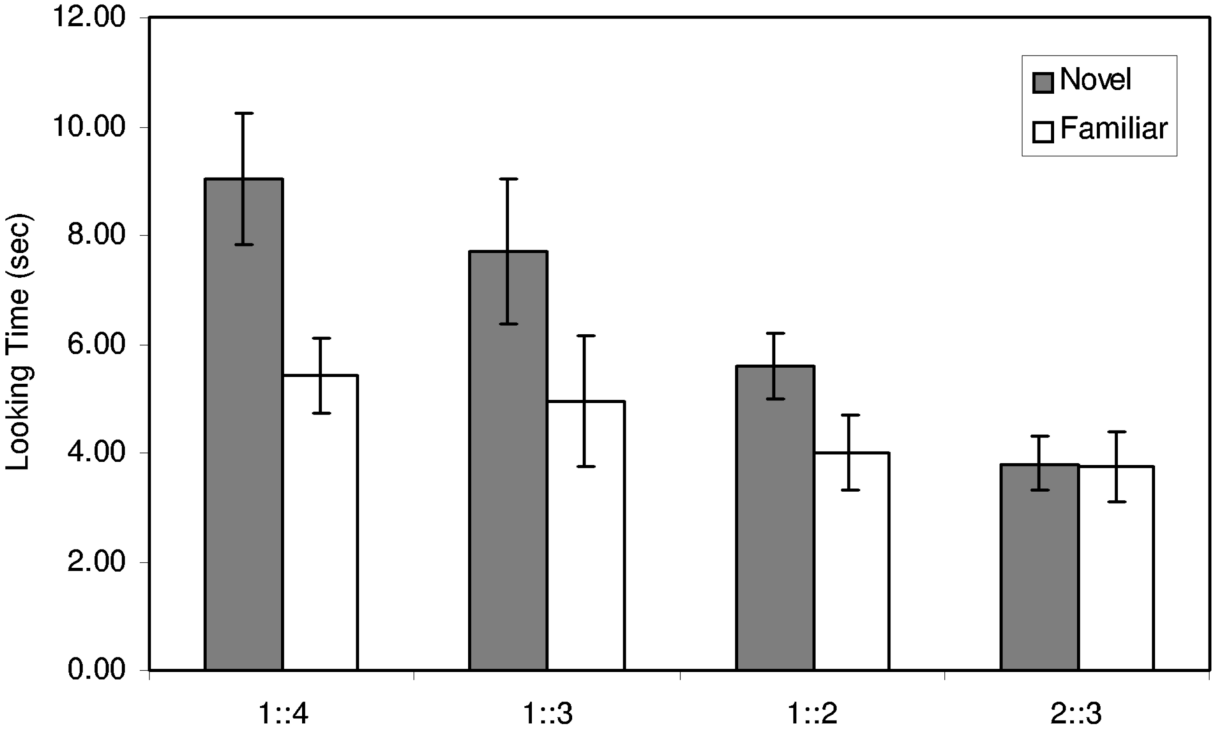

Figure 2.
Average looking times for infants in Experiment 1 to the novel and familiar surface areas by ratio condition.

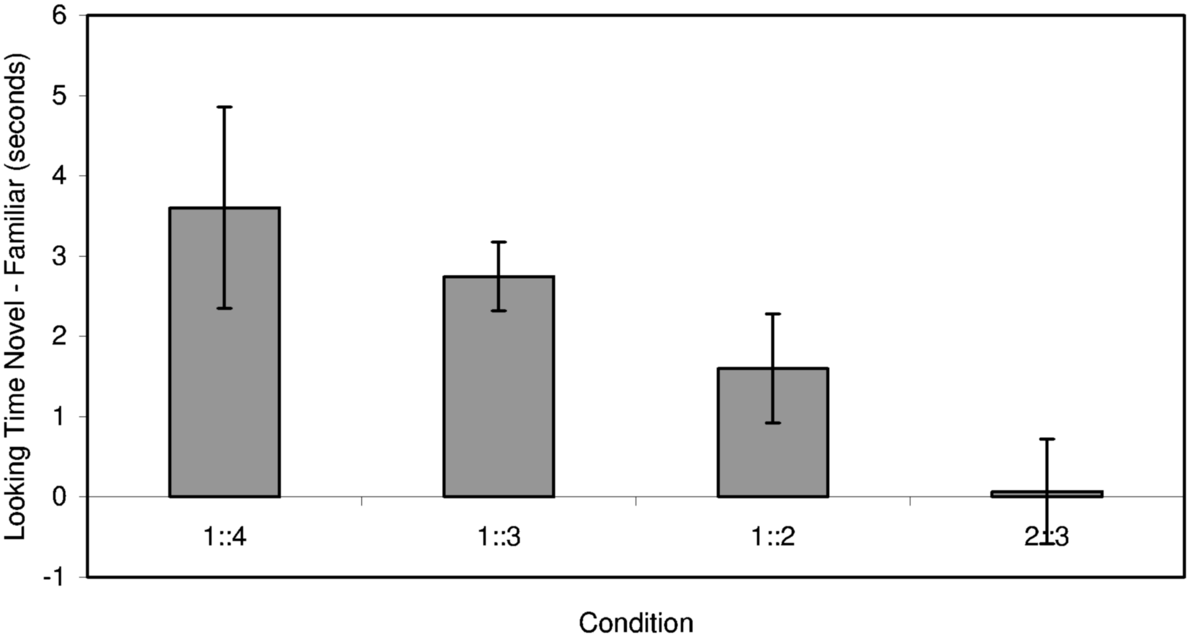

Figure 3.
Difference in looking time (novel-familiar) for the 4 conditions. Error bars reflect standard errors.

Table 1

Mean looking times and standard errors to novel and familiar test trials for each condition.

Condition	Novel Test Trials 1-3	Familiar Test Trials 1-3	First Novel Trial	First Familiar Trial
1:4	9.03 ± 1.22	5.43 ± 0.68	11.15 ± 1.45	6.99 ± 1.30
1:3	7.69 ± 1.34	4.94 ± 1.21	9.07 ± 2.68	4.46 ± 1.34
1:2	5.60 ± 0.6	4.00 ± 0.69	6.43 ± 1.17	3.08 ± 0.57
2:3	3.80 ± 0.51	3.74 ± 0.63	4.43 ± 0.82	4.54 ± 1.05