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Infants' auditory enumeration: Evidence for analog magnitudes in the small number range

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A B S T R A C T

Vigorous debate surrounds the issue of whether infants use different representational mechanisms to discriminate small and large numbers. We report evidence for ratio-dependent performance in infants' discrimination of small numbers of auditory events, suggesting that infants can use analog magnitudes to represent small values, at least in the auditory domain. Seven-month-old infants in the present study reliably discriminated two from four tones (a 1:2 ratio) in Experiment 1, when melodic and continuous temporal properties of the sequences were controlled, but failed to discriminate two from three tones (a 2:3 ratio) under the same conditions in Experiment 2. A third experiment ruled out the possibility that infants in Experiment 1 were responding to greater melodic variety in the four-tone sequences. The discrimination function obtained here is the same as that found for infants' discrimination of large numbers of visual and auditory items at a similar age, as well as for that obtained for similar-aged infants' duration discriminations, and thus adds to a growing body of evidence suggesting that human infants may share with adults and nonhuman animals a mechanism for representing quantities as "noisy" mental magnitudes.

1. Introduction

Over the past decade or so, there has been vigorous debate about whether young infants possess numerical knowledge. Researchers on one side of the debate argue that a representation of number is not present in the first year of life, but rather develops over the course of the first few years (Clearfield, 2004; Mix, Huttenlocher, & Levine, 2002; Mix, Levine, & Huttenlocher, 1997; Wakely, Rivera, & Langer, 2000). Researchers on the other side argue that infants not only represent numerosity (Brannon, 2005; Brannon, Abbott, & Lutz, 2004; Brannon & Roitman, 2003; Jordan & Brannon, 2006; Lipton & Spelke, 2003; Wood & Spelke, 2005a, 2005b; Wynn, 1995, 1998; Xu & Spelke, 2000), but also use their representations to make ordinal judgments (Brannon, 2002), compute the results of addition and subtraction operations (McCrink & Wynn, 2004; Wynn, 1992), and determine and discriminate ratios of two numerical values (McCrink & Wynn, 2007). Resolving this issue is critical if we are to understand the origins of numerical concepts and the developmental progression of these abilities.

1.1. Numerosity versus continuous variables

Much of the early research on infants' numerical abilities failed to control for non-numerical properties of the stimuli. For spatially arrayed stimuli, for example, properties such as contour length and surface area were often left to co-vary with number, rendering the results of some studies ambiguous as to whether infants were responding to number or some continuous property of the stimuli (Mix et al., 2002). Subsequent studies that either pitted number against continuous quantity or controlled for continuous

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quantity showed that infants are indeed sensitive to the continuous properties (e.g., contour length, surface area) of visual stimuli, and in some cases, respond to a change in continuous quantity but not number (Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Spelke, 2002, but see Feigenson, 2005). The same is true for temporally arrayed stimuli (e.g., event sequences), where researchers initially failed to completely control for all non-numerical properties of the sequences. Again, research pitting continuous quantities, such as duration of action, against number found that infants were sensitive to non-numerical properties of event sequences (Clearfield, 2004). Note, however, that subsequent research by Wood and Spelke (2005b) shows that infants can discriminate event sequences on the basis of number when non-numerical stimuli are properly controlled.

In fact, controlling for all of the properties that co-vary with number in a given stimulus set is quite difficult and with some displays is impossible (e.g., it is impossible to simultaneously control for both summed surface area and summed contour length of circular items while varying number of items). Nevertheless, recent research that has controlled for non-numerical properties suggests that like nonhuman animals and human adults, infants respond to a wide range of numerical stimuli, including objects, sounds, events, and groups, stationary items and moving items, as well as items presented simultaneously and items presented sequentially (e.g., Brannon et al., 2004; Feigenson, 2005; Jordan & Brannon, 2006; Lipton & Spelke, 2003; McCrink & Wynn, 2004; Wood & Spelke, 2005b; Wynn, Bloom, & Chiang, 2002; Xu & Spelke, 2000; cf. Mix et al., 2002). For example, both Xu and Spelke (2000) and Brannon et al. (2004) habituated 6-month-old infants to either 8 or 16 dots, with continuous properties (e.g., surface area, density, contour length) varying across trials. At test, infants were presented with 8 and 16 dots, on alternating trials. Importantly, the continuous properties that varied in habituation were held constant at test and therefore could not be used to discriminate the displays. Infants in both habituation groups preferred test displays with a new number of dots, indicating sensitivity to number of dots.[1]

In another study, Wynn et al. (2002) habituated 5-month-old infants to either *two* moving groups of three filled circles each traversing a display, or *four* moving groups of three circles each. Each group traversed the display at a differing (and varying) rate from the others, so that the overall configuration and outer perimeter of the set of groups in each display changed continuously. Moreover, the individual circles *within* each group underwent independent motion with respect to each other such that the overall configuration and perimeter of each group changed continuously. At test, infants were presented with displays containing two moving groups of four circles each on some trials, and four moving groups of two circles each on other trials. Design of stimuli was such that (a) the total number of circles – and therefore summed contour length, summed area, and density of circles – were equated across test displays; (b) the number of circles within each group – and therefore total contour length and area of the individual groups – were equated across habituation displays; and (c) the distance between individual circles within each group as well as that between circles from distinct groups varied extensively throughout presentation such that the outer perimeter of displays containing 4 groups was not reliably different from the outer perimeter of displays containing 2 groups. Thus, number of groups was the only reliable difference that distinguished "new-number" test displays from "habituated-number" test displays. Infants habituated to two groups looked longer at four groups in test, while infants habituated to four groups showed the opposite preference, indicating that infants were discriminating the number of groups in the displays.

Thus, while there is evidence that infants are sensitive to continuous perceptual variables such as contour length and cumulative area (Clearfield & Mix, 1999, 2001; Feigenson et al., 2002), there is also clear evidence that infants are sensitive to number.

1.2. Enumerating small and large numbers

The goal of the present study is to examine the nature of infants' early numerical abilities and in particular, what mechanism(s) may underlie these abilities. One candidate is the *analog magnitude* mechanism, which was originally developed to explain pigeons' and rats' ability to represent time and number (Gibbon, 1977; Meck & Church, 1983). Since then, research with adults and children suggests that humans also use analog magnitudes to represent time and number, as well as add and subtract numbers nonverbally (Barth, Kanwisher, & Spelke, 2003; Barth, La Mont, Lipton, & Spelke, 2005; Barth et al., 2006; Cordes, Gallistel, Gelman, & Latham, 2007; Cordes, Gelman, Gallistel, & Whalen, 2001; Dehaene, 1997; Gallistel & Gelman, 2005; Roitman, Brannon, Andrews, & Platt, 2007; Whalen, Gallistel, & Gelman, 1999). The representations are 'fuzzy' rather than exact, and variability increases in proportion to the number represented. As a result, the signature property of this mechanism is ratio-dependent discrimination: discriminability depends on the proportional, rather than the absolute, difference between two values, in accordance with Weber's law (Gallistel & Gelman, 1992, 2005; Meck & Church, 1983). Thus, it is easier to discriminate 10 from

[1] It is worth noting that a recent chapter by Clearfield (in press) argues that studies using the stimulus design of Xu and Spelke (2000) do not conclusively show that infants can discriminate large numbers of visual stimuli. In her chapter, she presents data suggesting that when pitted against each other, infants respond to changes in summed contour length, but not number, in a large number discrimination task. These new data would appear to present a challenge to previous studies reporting successful numerical discrimination for large numbers of visual stimuli. However, since the test stimuli in Clearfield's (in press) study differed in terms of summed surface area and density, as well as summed contour length, it is not clear that infants in those experiments were dishabituating to a change in summed contour length per se. Therefore, because Xu and Spelke (2000) (as well as other studies utilizing the same controls for non-numerical properties, e.g., Brannon et al., 2004; Xu, 2003; Xu et al., 2005) did control for summed surface area and density, it remains unclear whether infants are even sensitive to changes in summed contour length for large displays of visual items. As such, the recent work by Clearfield (in press) does not undermine the many previous studies showing successful large number discrimination for visual sets. Moreover, recent work by Cordes and Brannon (2008) finds that infants are more sensitive to changes in number than to changes in area/contour length, for both small- and large-number displays of multiple objects.

20 items (a 1:2 ratio) than 20 from 30 items (a 2:3 ratio), even though the absolute difference between the values (i.e., 10) is the same in both cases.

There is mounting evidence that infants possess an analog magnitude mechanism. For instance, infants' ability to discriminate audio-visual events differing in duration depends on the ratio of the durations. In one study, 6-month-old infants successfully discriminated durations differing by a 1:2 ratio, but not a 2:3 ratio, across two different time ranges (vanMarle & Wynn, 2006; see also Brannon, Suanda, & Libertus, 2007). In the number domain, infants' ability to discriminate large values is also ratio-dependent. In both the visual and auditory modalities, 6-month-olds reliably discriminate 4 from 8 and 8 from 16, but fail to discriminate 4 from 6 and 8 from 12 (Wood & Spelke, 2005b; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). Note that the same Weber fraction signature was found across the two modalities as well as for both time and number: 6-month-old infants discriminated values at a 1:2 ratio, but not a 2:3 ratio.[2] This ratio-dependent performance suggests that an analog magnitude mechanism may underlie infants' discrimination of large numbers of both visual and auditory items.

Recently, some researchers have suggested that while discrimination of large numbers relies on analog magnitude representations, discrimination in the small number range depends upon a different mechanism – one for tracking individual objects via "object files" (Feigenson, Carey, & Hauser, 2002; Feigenson, Dehaene, & Spelke, 2004; Lipton & Spelke, 2004; Xu, 2003). The *object file system* was developed to account for adults' ability to simultaneously track small numbers of visual objects. It consists of a limited number of attentional indexes, or "pointers", each of which can point to an object in the world, keeping track of it as it moves through space (Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, 1989; Trick & Pylyshyn, 1994). The signature property of this mechanism is its limited capacity. It can only track as many objects as it has indexes. In adults, the limit appears to be about four (Pylyshyn & Storm, 1988; Scholl, 2001; cf. Alvarez & Cavanaugh, 2004).

Infant researchers have recently adopted this mechanism to explain similar capacity limits in the number of objects infants can track in certain tasks (Feigenson & Carey, 2003; Feigenson et al., 2002). In one such task, infants watch an experimenter lower different numbers of crackers (one at a time) into two opaque cups. Once all of the crackers are hidden, the infant is allowed to crawl to the cup of her choice. Infants reliably choose the cup with more crackers, but only as long as there are no more than three crackers in either cup. This limit on the number of objects that can be represented and compared in memory has been termed the "set size signature" and its presence in a given task is taken as evidence that the object file system underlies performance on that task (Feigenson & Carey, 2003; Feigenson et al., 2002).

The most compelling evidence that infants use distinct mechanisms to represent small and large numbers comes from studies directly comparing infants' ability to discriminate small and large numbers of stimuli (Lipton & Spelke, 2004; Xu, 2003; see also Spelke, 2003). Using the same paradigm and stimulus controls as in Xu and Spelke's (2000) large number studies, Xu (2003) and Xu et al. (2005) showed that 6-month-old infants successfully discriminated large (4 vs. 8 and 16 vs. 32) but not small (1 vs. 2 and 2 vs. 4) numbers of dots, even though they differed by a discriminable 1:2 ratio. The same pattern of results was found for auditory stimuli. When comparing infants performance with small and large numbers of sounds, Lipton and Spelke (2004) found that 6-month-old infants successfully discriminated 4 from 8, but not 2 from 4, complex sounds.

How can we explain these surprising failures? Xu (2003) raised two possibilities: (1) the analog magnitude mechanism may not support discrimination of small numbers because the necessary computations are undefined for small values; or (2) object file representations may inhibit the output of the analog magnitude representations in situations where both are activated. The first possibility suggests that the analog mechanism simply cannot represent small values. The second suggests that although both mechanisms may represent small values, object tracking representations "trump" analog magnitude representations in the small number range. Indeed, if infants do possess an analog magnitude mechanism, it is peculiar that they would not use it to represent small values, since research with human adults and nonhuman animals suggests that analog magnitudes operate across the entire number range (Brannon & Roitman, 2003; Cantlon & Brannon, 2006; Cordes et al., 2001; Gallistel, 1990; cf. Hauser, Carey, & Hauser, 2000; Hauser, Dehaene, Dehaene-Lambertz, & Patalano, 2002).

Given this, Xu's (2003) first possibility seems unlikely. The computations necessary for representing large numbers operate over small numbers as well, at least in adults and nonhuman animals. The second possibility, that object files trump analog magnitudes in the small number range, seems more likely. One way to test for the existence of analog magnitudes in the small number range is to examine infants' numerical abilities in a different modality. Since object files are *visual object* representations, they should not be involved in the enumeration of non-object items and thus, should not be in competition with analog magnitude representations.

Lipton and Spelke (2004) used this approach by comparing 6-month-old infants' ability to discriminate small (two vs. four) and large (four vs. eight) numbers of complex sounds. As noted above, infants succeeded with the large values, but failed to discriminate the small values, suggesting that although infants possess an analog magnitude mechanism, it only operates over large values. Unfortunately, certain aspects of the methodology and stimuli used in that study could have interfered with infants' performance. First, instead of *habituating* infants to different numbers of sounds, infants were presented with a fixed

[2] Note also that the precision of analog magnitude representations increases with age. Two studies in the number domain (Lipton & Spelke, 2003; Lipton & Spelke, 2004) and two in the temporal domain (Brannon et al., 2007; vanMarle & Wynn, 2006) suggest that although infants are unable to discriminate values differing by a 2:3 ratio at 6 months, by 9 months, they can discriminate 2:3 ratios, but not 4:5 ratios. By adulthood, numerous studies suggest that the ratio of discriminability is 7:8 (Barth et al., 2003).

number (12) of familiarization trials in the first part of the experiment, leaving open the possibility that infants were not fully habituated when presented with the test stimuli. Second, and perhaps more important, is the fact that although there were sophisticated controls in place to eliminate non-numerical properties as a basis for discrimination, all properties were not strictly controlled. In particular, tempo (which was held constant during familiarization) was varied at test in such a way that the two test trial types were not equally familiar when compared to the average tempos experienced in familiarization. In other experiments, where the test tempos were equidistant from the average rates during familiarization, there were other properties that were not equidistant from the familiarized values (e.g., duration of individual sounds, duration of ISIs, ratio of sound/silence, etc.). Given this, it is premature to conclude that infants do not use analog magnitudes to represent small numbers of events.

The present study, therefore, examined infants' sensitivity to small numbers of auditory stimuli – two vs. four tones (1:2 ratio) and two vs. three tones (2:3 ratio). If we find ratio-dependent performance for small numbers of sounds (successful discrimination of two from four tones, but not two from three tones), this would provide evidence that analog magnitudes operate over small numbers in infants, just as they do in adults and nonhuman animals. On the other hand, if infants' analog magnitude mechanism does not represent small numbers at all, then infants are expected to fail in both cases, since object files do not operate over non-visual entities. The present study also tests a third alternative, which is that there may be an "auditory event file" system, analogous to the object file system, and with the same capacity limits (Hauser et al., 2002; see also Hommel, 1998, 2004). If infants possess such a mechanism, they should successfully discriminate two from three tones (because they fall within the set size limit), but not two from four tones (because four exceeds the capacity limit).

2. Experiment 1

Experiment 1 investigated 7-month-olds infants' ability to discriminate two from four tones, with continuous variables of the tone sequences controlled. Successful discrimination of small values differing by a 1:2 ratio in infants of this age would support the proposal that analog magnitudes can apply over small values in infancy.

2.1. Method

2.1.1. Participants

Sixteen infants (9 girls), with a mean age of 7m1d (range: 5m16d to 7m15d), participated in this experiment. Three additional infants were tested but excluded from the final sample due to fussiness (1 infant) or extreme disinterest (2 infants). Participants were identified from a commercial mailing list and recruited via telephone. The majority of participants were from White, middle class families living in New Haven County. Free parking was provided and all infants received a small gift for their participation.

2.1.2. Apparatus

Participants sat in an infant seat facing a puppet stage. The stage was surrounded on three sides by black curtains and illuminated from above. A separate black curtain could be lowered, occluding the entire stage, between each trial. A puppet sat in the center of the stage and emitted sound sequences on each trial. Parents sat next to their infants, facing away from the stage to avoid possible cueing.

A Macintosh iBook computer was used to play sound sequences through a small peripheral speaker placed inside of the puppet. A camera on the back of the stage recorded the infant's image, while a second camera situated above and behind the infant recorded an image of the stage. The output from both cameras was sent through a Videonics Digital Video Mixer and displayed (in a split-screen format) on a television monitor. All sessions were videotaped.

An experienced observer recorded looking times online with a Macintosh iBook computer using MacXHAB 1.4 software (Pinto, 1995). The observer was kept blind to the order of the test trials by listening to a masking tape through headphones, which were additionally covered by soundproof earmuffs. Since the observer could not hear the experimental sequences, and because looking time was measured from the end of each sequence, a light switch was employed to signal the observer to begin timing. We calculated inter-observer reliability for half of the participants (8 of 16) by correlating the online observer's looking times with those coded from the videotaped records by a second trained observer blind to the infants' experimental condition. Across these participants, inter-observer agreement was very high ($r = .98$).

2.1.3. Design

Approximately equal numbers of females and males were habituated to either two- or four-tone sequences. Three pairs of test trials followed in which infants were presented, on alternate trials, with two- and four-tone sequences. The order of test trials (*two,four* or *four,two*) was counterbalanced across infants and the dependent measure was looking time to the puppet following the end of each sequence.

2.1.4. Stimuli

We created and presented the sound sequences using SoundEffects 0.9.2 software for Macintosh (Ricci, 1994–1995). All sounds were pure sine waves, each of which had a unique pitch[3] (i.e., frequency in Hz) drawn from a range close to that of human speech (200–1300 Hz). Since each tone had a unique pitch, we had to control for melodic properties that infants might use to distinguish the sequences. We accomplished this in the following way: First, each tone in every habituation sequence had a unique pitch, giving each sequence a unique combination of pitches. Importantly, all sequences in habituation and test had the same average frequency (750 Hz). Second, adjacent tones within a sequence were dissonant and as such, did not pro-

[3] Pilot studies in the lab indicated that tone sequences in which pitch did not vary were not engaging to infants and infants had difficulty habituating.

duce melodic phrases that could be easily remembered and compared across trials. Third, to control for pitch contour, the habituation sequences followed one of two pitch patterns: (a) *rise* or (b) *fall* for the two-tone sequences, and (a) *rise-fall-rise* or (b) *fall-rise-fall* for the four-tone sequences. To ensure infants received approximately equal exposure to both patterns, the habituation sequences alternated between the two pitch patterns. At test, all sequences had a consistently rising pattern so that this dimension could not be used to discriminate the sequences.[4] Finally, the order in which infants experienced the habituation sequences (with the first trial exposing them to the endpoints of the pitch range, the second trial exposing them to the middle of the range, the third trial exposing them to the points just short of the endpoints, the fourth trial to points just outside the midpoints, and so forth) ensured all infants were equally exposed to the whole range of pitches.

Because we were interested in infants' ability to discriminate number per se, it was critical that we also rule out continuous temporal properties of the sequences as a basis for discrimination. To achieve this, we varied individual tone duration (.5 or 1 s), inter-tone interval (.5 or 1 s), and therefore tempo (i.e., rate), total tone duration, total interval duration, and overall duration throughout habituation, with the result that each habituation sequence had a unique, irregular temporal pattern (rhythm). The puppet was jiggled slightly and continuously (i.e., as if vibrating) through and slightly beyond the end of each sound sequence. This served to visually orient the infant towards the puppet stage during each sequence, as well as to demarcate the beginning and end of each sequence, which made it possible to equate the test sequences for total duration. (Note that since the test sequences were equated for total duration and the rate of jiggling was approximately equivalent on all trials, properties of the jiggling such as "amount of jiggling", "duration of jiggling", and "number of jiggles" could not be used to discriminate the test sequences).

During the test phase, the two-tone sequences had individual tone and interval durations of 1 s, while four-tone sequences had individual tone and interval durations of .5 s. Thus, test sequences were equated for total tone duration, total interval duration, and overall duration, and in both cases, the individual tone and interval durations were equally familiar. Since the duration of individual tones and intervals were held constant within each test sequences, the sequences both had a novel regular rhythm. Because all of the habituation sequences in both groups had unique irregular rhythms, both test sequences were equally novel in terms of rhythm. By the age tested here, infants are known to be sensitive to changes in the absolute timing parameters of a rhythm (e.g., Demany, McKenzie, & Vurpillot, 1977). However, the evidence remains somewhat mixed as to when infants become sensitive to changes in relative timing parameters of a rhythm, with some authors arguing that the ability does not emerge until approximately 12 months of age (Pickens & Bahrick, 1997). This issue is not relevant to the current studies since, as noted above, although rhythm changed from habituation to test, the regular rhythm used at test was equally novel for both habituation groups. Thus, even if infants detected the change in rhythm, it could not be used to discriminate the test sequences.

The tempo of the test sequences varied and was twice as fast for the four-tone test sequence (1 tone/s) compared to the two-tone sequence (.5 tone/s). However, even though the tempo of the four-tone sequence was more novel overall, it was equally so for both habituation groups, since the average tempo experienced in habituation (.67 tone/s) was the same for both groups. Thus, if infants respond to tempo, both habituation groups should look reliably longer following the four-tone test sequence. Total sequence duration, which was equated across the test sequences (4 s), was novel for both habituation groups. But, since infants habituated to four tones experienced sequences with an average duration of 6 s in habituation, while infants habituated to two tones experienced an average sequence duration of 3 s, the test sequences were somewhat more novel to infants habituated to four tones. Thus, if infants attend to total sequence duration, those habituated to four tones should look reliably longer overall than those habituated to two tones at test. For a detailed outline of the sound sequences used in Experiment 1, including all pitch and temporal parameters, see Appendix A.

2.1.5. Procedure

Following a brief introduction to the stage, curtain, and puppet, the habituation phase began in which infants were presented with 6 to 14 trials, each consisting of either two or four tones (depending on habituation group). Trials ended when an infant either: (1) looked away from the puppet for two consecutive seconds, or (2) looked for 30 cumulative seconds. The habituation criterion was calculated online and infants were considered habituated when (a) their looking times on three consecutive trials were less than half the sum of their looking times on the first three trials or (b) they completed fourteen trials. Once

Fig. 1. Photograph of the actual stage display used in the present experiments.

[4] Note that the four-tone test sequence had a novel pitch pattern that infants could use to discriminate the two- and four-tone test sequences. However, if infants used only this to discriminate the test sequences, both habituation groups should have looked longer at the 4-tone test sequence, which they did not.

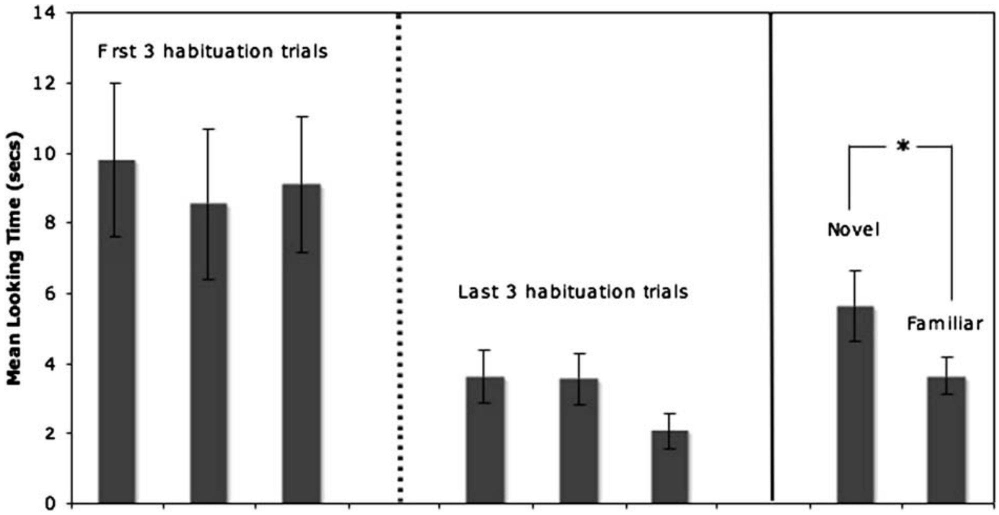

Fig. 2. Mean looking times (with standard error bars) to the first three and last three habituation trials and the novel and familiar test trials in Experiment 1. Infants' reliably discriminated small numbers of tones at test when they differed by a 1:2 ratio (two vs. four).

habituated, infants received six test trials alternating between two and four tones. See Fig. 1 for a view of the stage display and experimental setting.

2.2. Results

Fourteen out of sixteen infants reached habituation criterion (a) above (mean number of trials to criterion = 8). The two remaining infants received all 14 habituation trials. Infants looked longer at test when the puppet played a novel number of tones (M = 5.7 s, SD = 4.0) compared to a familiar number (M = 3.7 s, SD = 2.1) (See Fig. 2). A $2 \times 2 \times 2$ repeated measures ANOVA testing the effects of habituation group (*two* or *four*), trial order (*novel, familiar* or *familiar, novel*), and test trial kind (*novel* or *familiar*) revealed only a significant main effect of test trial kind, $F(1, 12) = 8.82$, $p < .012$, $\eta^2_G = 0.14$[5] (see Fig. 2). Non-parametric analyses confirmed this result. Thirteen of sixteen infants preferred the novel number at test (Sign test, $p < .005$). Repeating these analyses with the two infants who failed to habituate excluded revealed the exact same pattern of results for both the parametric (test trial kind: $F(1,10) = 7.65$, $p = .02$, $\eta^2_G = 0.15$) and non-parametric (12 of 14 preferred the novel number: $p < .01$) tests.

Because tempo varied at test, and previous work shows that infants are indeed sensitive to changes in tempo for auditory sequences (Pickens & Bahrick, 1995; Spelke, 1979; Trehub & Thorpe, 1989), we ran an additional analysis to rule out this variable. Because infants in both habituation groups experienced the same average tempo, both groups should have looked longer following the four-tone sequence since it was more novel than the two-tone sequence. This was not the case. A $2 \times 2 \times 2$ repeated measures ANOVA with habituation group (*two* or *four*) and trial order (*two,four* or *four,two*) as between subject factors, and Trial Kind (*two* or *four*) as a within subject factor, revealed only one significant effect – an interaction between Habituation group and test trial type, $F(1,12) = 9.62$, $p < .01$ – providing more support for the conclusion that infants were discriminating the number of tones. Infants habituated to two tones looked longer following the four-tone test sequence (M = 7.4 s, SD = 4.4) than the two-tone test sequence (M = 4.2 s, SD = 2.7), while infants habituated to four tones preferred two tones (M = 4.0 s, SD = 3.1) over four-tone (M = 3.2 s, SD = 1.3) at test. Although infants overall looked longer at the four-tone (M = 5.3 s, SD = 3.8) than the two-tone (M = 4.1 s, SD = 2.8) sequences, the main effect of Trial Kind was not significant ($F[1,12] = 3.37$, $p > .05$). Thus, infants did not appear to respond to the change in tempo in this experiment.[6]

This same analysis also rules out total sequence duration as a basis for infants' discrimination. Recall that the change in total duration from habituation to test was greater for infants habituated to four tones than those habituated to two tones. If infants were sensitive to this change, those habituated to four tones should have looked longer overall at both test sequences. However, the main effect of habituation group was not significant ($F[1,12] = 3.06$, $p > .05$). In fact, infants habituated to two tones looked longer overall (M = 5.8 s, SD = 3.6) than those habituated to four tones (M = 3.6 s, SD = 2.2). Indeed, it is unlikely that infants would have been able to discriminate the sequence durations at the ratios available to them here. Work by vanMarle and Wynn (2006) shows that infants of roughly this same age (6 months) fail to discriminate tones differing in duration by a 2:3 ratio. The ratios here were

[5] As a measure of effect size, we used η^2_G (generalized eta squared). η^2_G is recommended over *eta squared* (η^2) and *partial eta squared* ($\eta^2{}_P$) for effects obtained in analyses with repeated measures because eta squared and partial eta squared can give biased estimates of the effect size that are larger than would be obtained in the same study using a between subjects design (Olejnik & Algina, 2003). Note that for η^2_G, .02 is considered a small effect, .13 a medium-sized effect, and .26 a large effect (Bakeman, 2005).

[6] When we ran this same analysis excluding the two infants who failed to habituate, we obtained the same exact pattern of results. The only significant effect was the interaction between Habituation Group and Test Trial Type ($F(1,10) = 8.31$, $p < .02$) and the main effect of Trial Kind was not significant ($F[1,10] = 1.63$, $p > .05$).

that close and closer (2:3 for infants habituated to four tones, 3:4 for infants habituated to two tones), making it unlikely that infants would have been able to discriminate the test sequences based on this dimension.

2.3. Discussion

Infants discriminated the two- and four-tone test sequences even with non-numerical properties controlled or statistically ruled out, suggesting that they were responding based on number of tones. This is inconsistent with Lipton and Spelke's (2004) results in which infants failed to discriminate two from four sounds. However, it is consistent with previous research in which 6-month-old infants discriminated between large numbers of visual and auditory items at a 1:2 ratio (e.g., Lipton & Spelke, 2003, 2004; Xu & Spelke, 2000). The present results therefore provide preliminary support for the proposal that an analog magnitude mechanism underlies the representation of both small and large numbers in infancy.

3. Experiment 2

Contrary to previous research (Lipton & Spelke, 2004), Experiment 1 suggests that the same mechanism may underlie infants' discrimination of large and small numbers of auditory stimuli. However, evidence for analog magnitudes in the small number range depends not only infants' success with small numbers differing by a 1:2 ratio (at 6 months of age), but also their failure with small numbers differing by a 2:3 ratio. Experiment 2 tested this by asking whether infants can discriminate between sequences containing either two or three tones, again with non-numerical variables controlled.

3.1. Method

3.1.1. Participants

Sixteen infants (8 girls) with a mean age of 6m25d (range: 6m4d to 7m13d) participated in this experiment. Two additional infants were tested, but excluded from the final sample due to equipment failure (1 infant) or sibling interference (1 infant). We recruited the sample in the same manner as described above and participants were again predominantly White and middle class. Free parking was provided and all infants received a small gift for their participation.

3.1.2. Apparatus

We used the same stage apparatus and puppet from Experiment 1.

3.1.3. Design

Equal numbers of females and males were habituated to either two or three tones. Six test trials followed in which infants were presented with sequences of two and three tones (on alternating trials). The order of test trials (*two,-three* or *three,two*) was counterbalanced, and as before, the dependent measure was looking time to the puppet following the completion of each sound sequence. We again calculated inter-observer reliability for half of the participants and again, it was very high ($r = .98$).

3.1.4. Stimuli

Sound sequences were created and presented using the same software as in Experiment 1 and were the same in all respects except those noted here. In habituation, the two possible pitch patterns were: (a) *rise* or (b) *fall* for the two-tone sequences, and (a) *rise-fall* or (b) *fall-rise* for the three-tone sequences. Temporal factors were controlled as before except that individual tone durations and inter-tone intervals were .67 or 1 s. As in Experiment 1, tempo, total tone duration, total interval duration, and overall duration varied throughout the habituation phase, while the test sequences were equated for total tone duration, total interval duration, and overall duration. See Appendix B for details about the sound sequences in this experiment.

Rhythm, tempo, and total sequence duration were managed in the same fashion as in Experiment 1. Each habituation sequence had a unique, irregular rhythm, while both test sequences had the same, regular rhythm. As a result, both test sequences were equated and equally novel in terms of rhythm, making it so infants could not discriminate the test sequences along this dimension. As in Experiment 1, both habituation groups received sequences with the same average tempo (.6 tone/s), while both test sequences differed from each other and the habituation sequences along this dimension (two-tone = .5 tone/s; three-tone = .75 tone/s). If infants respond to tempo, both habituation groups should look reliably longer on the three-tone test sequence since it was more novel. Total sequence duration was again equated between the test sequences (4 s), but novel for both habituation groups (though by smaller amounts than in Experiment 1). Specifically, infants habituated to two tones heard sequences that averaged 3.32 s in duration, while those habituated to three tones heard sequences that averaged 4.98 s in duration. If they respond to a change in total sequence duration, infants habituated to three tones should look reliably longer overall compared to infants habituated to two tones, since the three-tone test sequence was slightly more novel on this dimension than the two-tone test sequence.

3.1.5. Procedure

The procedure was identical to Experiment 1.

3.2. Results

All sixteen infants reached habituation criterion (a) (see *Procedure* in Experiment 1 – average number of trials to this criterion = 8). In contrast to Experiment 1, infants did not differentiate between the novel and familiar numbers at test, looking about equally following the novel (M = 5.6 s, SD = 6.4) and the familiar (M = 6.0 s, SD = 4.7) test sequences (Fig. 3). A 2 × 2 × 2 repeated measures ANOVA testing the effects of habituation group (*two* or *three*), trial order (*novel,familiar* or *familiar,novel*), and test trial kind (*novel* or *familiar*) revealed no significant effects. Critically, the main effect of test trial kind was non-significant, $F(1, 12) = .05$, $p > .05$, $\eta^2_G = 0.002$, indicating that infants

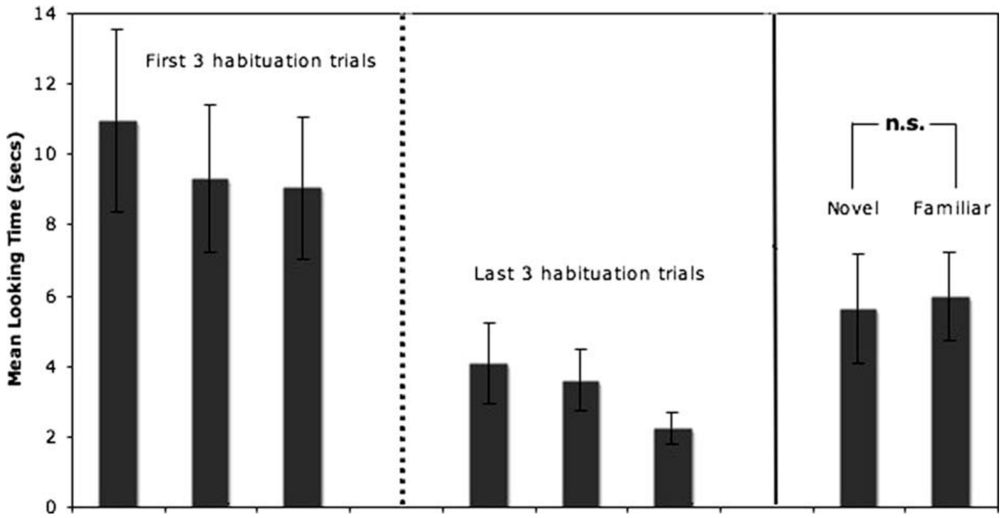

Fig. 3. Mean looking times (with standard error bars) to the first three and last three habituation trials and the novel and familiar test trials in Experiment 2. Infants failed to discriminate small numbers of tones when they differed by a 2:3 ratio (two vs. three).

did not discriminate between the test sequences. Non-parametric analyses confirmed these results – only 7 of 16 infants preferred the novel number at test (Sign test = $p > .8$).

To test whether infants were sensitive to tempo and/or total sequence duration, we conducted a $2 \times 2 \times 2$ repeated measures ANOVA with habituation group (*two* or *three*) and trial order (*two,three* or *three,two*) as the between subject factors, and test trial kind (*two* or *three*) as the within subject factor. There were no significant effects or interactions. Thus, neither the main effect of Trial Kind ($F[1,12] = .07$, $p > .05$) nor the main effect of habituation group ($F[1,12] = 3.06$, $p > .05$) were significant, suggesting that infants failed to respond to tempo and total sequence duration, respectively. In addition, since the interaction between habituation group and Trial Kind ($F[1,12] = .05$, $p > .05$) did not reach significance, this analysis further confirms that infants did not discriminate the test sequences on the basis of number.

3.3. Discussion

Despite the fact that infants in this experiment were tested in an identical procedure, with the same temporal and pitch controls, they showed no evidence of discriminating two from three auditory tones. Thus, as has been found with large numbers (Lipton & Spelke, 2003; Xu & Spelke, 2000), infants in Experiments 1 and 2 successfully discriminated small numbers at a 1:2, but not a 2:3 ratio, suggesting that, like adults and nonhuman animals, infants can represent small numbers with analog magnitudes. Note that these data are inconsistent with the possibility that infants use a capacity limited, auditory event file system to enumerate small numbers of auditory events, as has been proposed for nonhuman primates (Hauser et al., 2002). If infants used such a system, they should have successfully discriminated two from three tones, but not two from four tones (because four is outside the set size limit), which is precisely the opposite of the present results.

4. Experiment 3

We conducted a third experiment to rule out the possibility that infants in Experiment 1 were using non-numerical cues to discriminate the test sequences. Since the four-tone sequences in Experiment 1 had twice as many unique pitches compared to the two-tone sequences, it is possible that infants' success in that experiment was due to the greater melodic variety in the four-tone sequences. To examine this possibility, we varied the *number of pitches* in each sequence (one or two) while holding the *number of tones* constant (i.e., all sequences had four tones). If infants were simply responding to the greater variety of the four-tone sequences in Experiment 1, then they should differentiate between the sequences in this experiment on the basis of melodic variety. However, if they were responding to the change in number of tones, then they should fail to discriminate between the test sequences in this experiment.

4.1. Method

4.1.1. Participants

Sixteen infants (8 girls) with a mean age of 7m1d (range: 6m4d to 7m15d) participated in this experiment. Four additional infants were tested, but excluded from the final sample due to fussiness/disinterest (2 infants), sibling interference (1 infant), or being more than four weeks premature (1 infant). We recruited the sample in the same manner as before and participants were again predominantly White and middle class. Free parking was provided and all infants received a small gift for their participation.

4.1.1. Apparatus

We used the same stage apparatus and puppet as in the first two experiments.

4.1.2. Design

Equal numbers of females and males were randomly assigned to one of two habituation conditions in which they were habituated to sequences containing either one pitch (e.g., AAAA) or two pitches (e.g., ABAB). Six test trials followed in which we presented infants (on alternating trials) with sequences containing one (i.e., YYYY) and two (i.e., XXZZ) pitches. The order of test trials (*one,two* or *two,one*) was counterbalanced, and as before, the dependent measure was looking time to the puppet following the completion of each sound sequence. We calculated inter-observer reliability for half of the participants and it was again high ($r = .94$).

4.1.3. Stimuli

Sound sequences were created and presented using the same software as in the first two experiments and were the same in all respects except those noted below. Instead of varying number of tones between habituation and test, we held the number of tones constant and varied only the number of pitches in each sequence. Thus, the one-pitch habituation sequences consisted of four tones, all with the same pitch (e.g., AAAA, BBBB, CCCC, etc.). To keep infants' interest, the pitch of the tones was different on each habituation trial. The two-pitch habituation sequences also consisted of four tones, but contained two pitches played in an alternating pattern (e.g., ABAB, CDCD, EFEF, etc.). As in the one-pitch sequences, the pitches used in the two-pitch sequences varied across trials to maintain infants' interest. There were two types of test sequences, one-pitch and two-pitch. The one-pitch test sequences consisted of four tones all played at the same pitch (i.e., YYYY), which was the average of the all the pitches heard in habituation (750 Hz). The two-pitch test sequences had four tones consisting of two pitches. But unlike in habituation, the pitches were played in pairs, rather than in alternation (i.e., XXZZ), and the frequencies of the pairs of tones (690 and 810 Hz) together averaged to 750 Hz (the average pitch of the tones heard in habituation). We chose to pair, rather than alternate, the two pitches so infants could respond to the change in *melodic variety* or *number of pitches*, but not a difference in pitch contour, as pitch contour would be novel for both habituation groups.

Individual tone duration (.5 or 1 s), inter-tone interval (.5 or 1 s), and therefore tempo, total tone duration, total interval duration, and overall duration were varied throughout the habituation phase in exactly the same fashion as they were in the four-tone sequences in Experiment 1. At test, tone and interval duration was always .5 s. Consequently, the one- and two-pitch sequences were temporally identical throughout both habituation and test. As a result, neither rhythm, nor tempo, nor total sequence duration could be used to discriminate the test sequences. See Appendix C for detailed information about the sound sequences in this experiment.

4.1.4. Procedure

The procedure was identical to Experiment 1.

4.2. Results

Fourteen of sixteen infants reached habituation criterion (a) (see *Procedure* in Experiment 1, average number of trials to this criterion = 9). The two remaining infants received all 14 habituation trials. Infants' mean looking times indicated that they did not differentiate between the novel (M = 3.1 s, SD 2.0) and familiar (M = 3.3 s, SD = 2.5) number of pitches at test (see Fig. 4). A $2 \times 2 \times 2$ repeated measures ANOVA testing the effects of habituation group (*one-pitch* or *two-pitch*), trial order (*novel,familiar* or *familiar,novel*), and test trial kind (*novel* or *familiar*) revealed only a marginally significant effect of trial order ($F(1, 12) = 5.0$, $p = .06$). Infants who received test trials in the *familiar,novel* order looked longer overall (M = 4.3 s) than infants who received test trials in the opposite order (M = 2.4 s). Importantly, the effect of test trial kind did not approach significance, $F(1, 12) = .14$, $p > .05$, $\eta^2_G = 0.007$. Non-parametric analyses revealed a similar pattern – 8 of 16 infants preferred the Novel number of pitches at test (Sign test, $p = .60$). Repeating the parametric (test trial kind: $F(1,10) = .12$, $p > .05$, $\eta^2_G = 0.006$) and non-parametric (7 of 14 infants preferred the novel number: $p = .61$) analyses excluding the two infants who failed to habituate revealed the same pattern of results, except that the main effect of trial order was no longer marginally significant ($F(1, 10) = 3.0$, $p = .11$).

4.3. Discussion

Infants in this experiment did not differentiate between sequences with different numbers of pitches. Thus, it seems unlikely that infants in Experiment 1 were discriminating based on the greater melodic variety in the sequences with more tones. Rather, the results of Experiments 1 and 2 suggest that infants can use analog magnitudes to represent small numbers of sounds.

5. General discussion

The results of Experiments 1 and 2, to our knowledge, provide the first evidence of ratio-dependent performance in infants in the small number range. Given that the discrimination function obtained here with small numbers of auditory stimuli is the same as that found for large numbers of visual and auditory stimuli, these results add to a growing body of evidence that infants represent number via analog magnitudes. This does not preclude the possibility that additional processes (i.e., the object file system) contribute to infants' discrimination of small sets of visual items, but it does suggest that the analog magnitude mechanism can and does represent small values, at least in the auditory domain. As such, the present results are at odds with those of Lipton and Spelke (2004) who found that infants failed to discriminate two from four complex sounds. As discussed earlier, it is possible that infants failed in that experiment not because analog magnitude representations are restricted to large values, but because certain stimulus properties (e.g., rate, sound duration, ratio of sound to silence) were not adequately controlled.

These studies also speak against the claim that young infants do not possess any truly numerical abilities (Clearfield & Mix, 1999, 2001; Mix et al., 2002; Simon, 1997, 1999). Since continuous temporal and melodic attributes of the sequences were either controlled or statistically

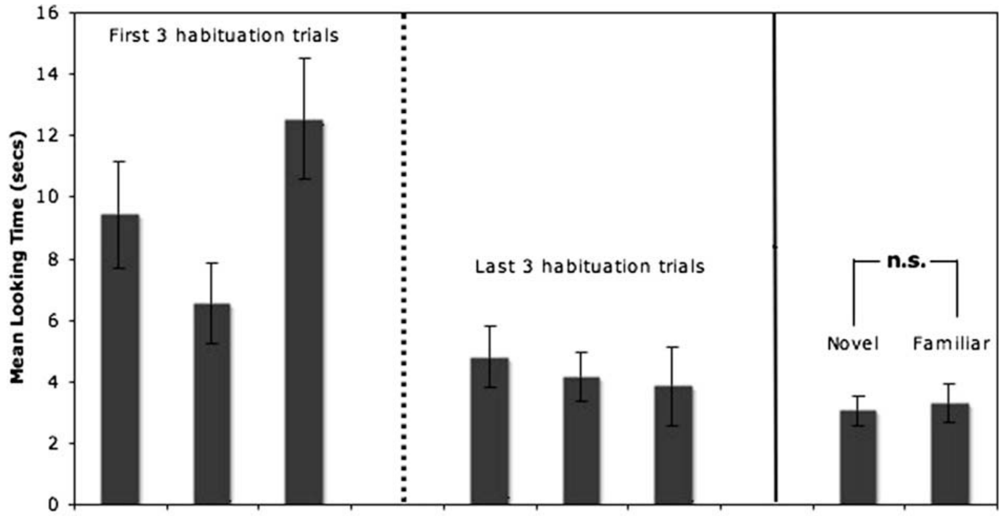

Fig. 4. Mean looking times (with standard error bars) to the first three and last three habituation trials and the novel and familiar test trials in Experiment 3. Infants did not discriminate the test sequences on the basis of melodic contour or number of pitches. Infants looked about equally regardless of whether the puppet played a novel or familiar number of pitches.

ruled out, it is unlikely that infants' discrimination was based on continuous variables in Experiment 1. Moreover, since infants here enumerated momentary auditory entities, rather than enduring visual objects, these results cannot be explained by appeal to object tracking processes or other visuo-spatial processing mechanisms purported to underlie infants' discrimination of small visual sets (Feigenson et al., 2002; Simon, 1999). Nonetheless, we believe it is quite possible that for visual objects, the object file system is operative in infants and that the outputs of such processes may compete with, or override, outputs of the analog magnitude mechanism in the visual modality. Thus, we do not see our findings here as inconsistent with the suggestion that for small numbers of visual objects, an object-based representation system applies. Rather, we view our findings as an existence proof that the analog magnitude system applies to the full range of numerical values and is not inherently restricted to representing only large numerical values.

It is also worth noting that although the present data constrain the format of representation that infants appear to use to represent small number of auditory items, this study does not speak to the nature of the mechanism itself or the processes by which the analog representations are formed. There have been several models put forth in the literature over the last few decades, all of which are properly called "analog magnitude" models, but which vary (sometimes greatly) with respect the processes involved in constructing and maintaining analog magnitude representations (e.g., Barth et al., 2003; Church & Broadbent, 1990; Dehaene & Changeux, 1993; Gallistel, 1990; Gallistel & Gelman, 2000; Meck & Church, 1983). Recent work by Wood and Spelke (2005a) has begun to tap into what processes may be active in infants, suggesting that for visual displays in which the items are presented simultaneously, the analog magnitude mechanism appears to enumerate the items in parallel, rather than iteratively. Parallel processing however, cannot account for the present results since the tones were not available simultaneously, suggesting that the analog magnitude mechanism may be able to enumerate items in parallel and in an iterative fashion, depending on the nature of the input. Since a full understanding of infants' numerical abilities requires not only identifying the format of their representations, but also the nature of the processes and mechanisms which produce them, we expect that future studies will shed light on both aspects of this question.

In conclusion, the present results provide preliminary evidence supporting the hypothesis that infants can use analog magnitudes to represent small numbers, at least in the auditory domain. The same Weber fraction found (in 6-month-old infants) for large numbers of visual and auditory stimuli, as well as duration, was found here. Seven-month-old infants reliably discriminated two from four tones, but not two from three tones, showing the ratio signature of the analog magnitude system, rather than the set size signature of the object file system. Taken together with previous findings, the present results thus shed light on the origins of humans' numerical abilities by providing further evidence that infants may share with adults and nonhuman animals a mechanism for representing quantity via 'noisy' mental magnitudes.

Acknowledgements

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Appendix A

Tone sequences – Experiment 1

2-Tone Sequences			4-Tone Sequences		
Frequency (Hz)	Temporal Schematic (total duration in seconds)		Frequency (Hz)	Temporal Schematic (total duration in seconds)	
200 - 1300		(2.5)	200-1260-240-1300		(6.0)
700 - 800		(3.5)	760-700-800-740		(6.0)
1280 - 220		(3.0)	1240-220-1280-260		(6.0)
820 - 680		(3.5)	680-780-720-820		(6.0)
1220 - 280		(3.5)	280-1180-320-1220		(5.5)
620 - 880		(2.5)	840-620-880-660		(6.0)
300 - 1200		(2.5)	1160-300-1200-340		(6.5)
900 - 600		(2.5)	600-860-640-900		(6.0)
1140 - 360		(3.0)	360-1100-400-1140		(6.0)
960 - 540		(3.5)	920-540-960-580		(5.5)
380 - 1120		(3.0)	1080-380-1120-420		(6.0)
520 - 980		(3.0)	520-940-560-980		(6.0)
440 - 1060		(3.0)	440-1020-480-1060		(6.5)
1040 - 460		(3.0)	1000-460-1040-500		(6.0)
TEST			**TEST**		
690 - 810		(4.0)	690-730-770-810		(4.0)

Note: Every sequence began with a tone and ended with silence. Short horizontal lines (–) = .5 s of tone/silence. Long horizontal lines (—) = 1 s of tone/silence.

Appendix B

Tone sequences – Experiment 2

2-Tone Sequences			3-Tone Sequences		
Frequency (Hz)	Temporal Schematic (total duration in seconds)		Frequency (Hz)	Temporal Schematic (total duration in seconds)	
200 - 1300		(2.98)	1260-1300-200		(4.64)
700 - 800		(3.66)	740-700-760		(5.32)
1280 - 220		(3.32)	260-220-1280		(4.64)
820 - 680		(3.66)	780-820-680		(5.32)
1220 - 280		(3.66)	1180-1220-280		(4.64)
620 - 880		(2.98)	840-620-660		(4.98)
300 - 1200		(2.98)	1160-300-1200		(5.32)
900 - 600		(2.98)	640-900-600		(4.98)
1140 - 360		(3.32)	360-1140-400		(4.98)
960 - 540		(3.66)	920-540-960		(4.98)
380 - 1120		(3.32)	1080-420-1120		(4.98)
520 - 980		(3.32)	520-980-560		(4.98)
440 - 1060		(3.32)	440-1060-480		(4.98)
1040 - 460		(3.32)	1000-460-1040		(4.98)
TEST			**TEST**		
690 - 810		(4.0)	690-750-810		(4.0)

Note: Every sequence began with a tone and ended with silence. Short horizontal lines (–) = .67 s of tone/silence. Long horizontal lines (—) = 1 s of tone/silence.

Appendix C

Tone sequences – Experiment 3.

2-Tone Sequences			3-Tone Sequences		
Frequency (Hz)	Temporal Schematic (total duration in seconds)		Frequency (Hz)	Temporal Schematic (total duration in seconds)	
200 - 1300		(2.98)	1260-1300-200		(4.64)
700 - 800		(3.66)	740-700-760		(5.32)
1280 - 220		(3.32)	260-220-1280		(4.64)
820 - 680		(3.66)	780-820-680		(5.32)
1220 - 280		(3.66)	1180-1220-280		(4.64)
620 - 880		(2.98)	840-620-660		(4.98)
300 - 1200		(2.98)	1160-300-1200		(5.32)
900 - 600		(2.98)	640-900-600		(4.98)
1140 - 360		(3.32)	360-1140-400		(4.98)
960 - 540		(3.66)	920-540-960		(4.98)
380 - 1120		(3.32)	1080-420-1120		(4.98)
520 - 980		(3.32)	520-980-560		(4.98)
440 - 1060		(3.32)	440-1060-480		(4.98)
1040 - 460		(3.32)	1000-460-1040		(4.98)
TEST			**TEST**		
690 - 810		(4.0)	690-750-810		(4.0)

Note: Every sequence began with a tone and ended with silence. Short horizontal lines (–) = .5 s of tone/silence. Long horizontal lines (—) = 1 s of tone/silence.

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