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Infant auditory short-term memory for non-linguistic sounds

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ABSTRACT

This research explores auditory short-term memory (STM) capacity for non-linguistic sounds in 10-month-old infants. Infants were presented with auditory streams composed of repeating sequences of either 2 or 4 unique instruments (e.g., flute, piano, cello; 350 or 700 ms in duration) followed by a 500-ms retention interval. These instrument sequences either stayed the same for every repetition (Constant) or changed by 1 instrument per sequence (Varying). Using the head-turn preference procedure, infant listening durations were recorded for each stream type (2- or 4-instrument sequences composed of 350- or 700-ms notes). Preference for the Varying stream was taken as evidence of auditory STM because detection of the novel instrument required memory for all of the instruments in a given sequence. Results demonstrate that infants listened longer to Varying streams for 2-instrument sequences, but not 4-instrument sequences, composed of 350-ms notes (Experiment 1), although this effect did not hold when note durations were increased to 700 ms (Experiment 2). Experiment 3 replicates and extends results from Experiments 1 and 2 and provides support for a duration account of capacity limits in infant auditory STM.

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Introduction

Short-term memory (STM), or working memory, allows information to be stored temporarily and used quickly for tasks requiring some amount of online processing (Baddeley & Hitch, 1974). One distinct feature of STM is that it is highly capacity limited; thus, the amount of information an individual is able to hold or manage is highly constrained. Although these limits have been well-studied in adults, far less research has examined such limits in young children, particularly infants.

Deficits in working memory have been tied to several important cognitive deficits, including inattention, distractibility, and attention deficit hyperactivity disorder (ADHD) (Martinussen & Tannock, 2006; Rapport, Orban, Kofler, & Friedman, 2013), reading (Gathercole, Tiffant, Briscoe, Thorn, & ALSPAC team, 2005; Siegel & Ryan, 1989), language (Archibald & Gathercole, 2006; Weismer et al., 2000), and math (Alloway & Passolunghi, 2011; Zheng, Swanson, & Marcoulides, 2011), and working memory has been linked with the ability to acquire new knowledge and skills, particularly in the development of reading and language (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Atkins & Baddeley, 1998; Service, 1992). This profusion of working memory-related findings has schools scrambling to include working memory assessments in an attempt to identify children at risk for deficit (e.g., Normand & Tannock, 2014). Clearly, intervention attempts would be facilitated by earlier detection of deficits marked by low working memory capacity.

Auditory working memory capacity is typically assessed through verbal tasks, with most studies focused on memory for digits or pronounceable nonwords and aimed at the process of language acquisition (e.g., Baddeley, Gathercole, & Papagno, 1998; Gathercole & Baddeley, 1989; Gathercole, Hitch, Service, & Martin, 1997; Hoff, Core, & Bridges, 2008). These studies have revealed impressive development during an important period of language acquisition and have also revealed correlations between later vocabulary development and early auditory/phonological working memory capacity (Gathercole & Baddeley, 1989), although the direction of the relationship is debated (Gupta & Tisdale, 2009; Snowling, Chiat, & Hulme, 1991). These studies have critically informed research aimed at understanding the development of language and the interactive influence of lower cognitive functions on subsequent development.

A few studies have addressed the specific question of capacity (e.g., Gathercole & Pickering, 1999) but typically have used language-based memory items to assess limits in verbal working memory. In addition to requiring participants old enough to talk and follow instructions, tasks that rely on verbal responses reflect performance across a number of domains beyond memory, including temperament, attention, and speech. For example, phonological working memory tasks often require that children repeat nonwords after the experimenter (Hoff et al., 2008), which likely places additional cognitive and motor demands on children. These tasks also rely heavily on children's existing knowledge of the phonological rules of the language (Gathercole, 2006). The vast majority of work on working memory has examined either visuospatial objects or auditory–verbal objects (words and nonwords). Very little work has examined auditory information that cannot be verbally encoded, essentially confounding estimates of auditory STM capacity with issues pertaining to language fluency and expertise—a particularly thorny issue for developmental researchers. Much of this work reveals important links between early STM development and later language proficiency. However, it is unclear whether the relation is being driven by limits in phonological STM or more domain-general STM resources. For example, in their longitudinal research, Gathercole and colleagues (2005) found evidence for separate effects of phonological and general STM systems. In particular, children who were rated as having poor phonological STM at 5 years but not at 8 years of age showed more impairment on measures of language proficiency than children with persistent phonological impairment (Gathercole et al., 2005). The authors reasoned that early measures of phonological STM are disproportionately influenced by tertiary STM systems due to the relative underdevelopment of lexical support systems. Clearly, auditory STM is linked to vocabulary development, language acquisition, and language proficiency, although it is currently unclear exactly how.

In addition to concerns of language and memory confounds, there is reason to believe that estimates of STM capacity differ across verbal and non-verbal tasks. For example, in work with adults, Li, Cowan, and Saults (2013) found significantly reduced STM capacity for tones relative to visual and verbal STM capacity. Increasing tone distinctness only partially ameliorated this effect, indicating that reduced capacity was not solely a function of perceptual similarity. Similarly, Schulze and Tillmann (2013) examined working memory for pitch, timbre, and words and found clear evidence for the dissociation of linguistic and non-linguistic working memory stores. Clearly, verbal and non-verbal components of STM performance are dissociable in adults and are likely dissociable in children as well. Whether this reflects independent functioning across two unique memory stores or interdependent functioning within a single unitary memory store remains to be seen. Nonetheless, there is sufficient reason to suspect that auditory STM for non-linguistic sounds is an important dissociable component of acoustic memory. Fortunately, STM for non-linguistic information may be significantly more tractable in preverbal infants, offering researchers an earlier glimpse into developing frameworks of cognition.

Here we present work that directly examined infant auditory STM capacity for *non-linguistic* sounds during the critical first year of language development. Recent work examining visual STM capacity in infants has demonstrated that visual STM undergoes important changes during the second half of the first year of life, when attention and memory systems are changing rapidly (Oakes, Hurley, Ross-Sheehy, & Luck, 2011; Oakes, Messenger, Ross-Sheehy, & Luck, 2009; Oakes, Ross-Sheehy, & Luck, 2006; Ross-Sheehy, Oakes, & Luck, 2003, 2011). Both auditory and visual STM memory capacities depend critically on their respective input systems, a factor that is important to consider when making comparisons across domains. Although the infant cochlea itself is largely mature by birth, its organization (and thus infant acoustic abilities) continues to develop during infancy. However, frequency discrimination and high-frequency resolution both develop rapidly and are nearly adult-like by 6 months of age (Olsho, Koch, & Holpin, 1987; Spetner & Olsho, 1990), although low-frequency resolution and the ability to detect signals in the presence of noise continue to develop for several years (Werner, 2007). Clearly by 10 months, infants are able to detect and respond to most sounds in their acoustical environment and should be able to process and remember simple and complex sounds. Although we have made much progress in understanding STM in the visual domain (Oakes et al., 2006, 2009, 2011; Ross-Sheehy et al., 2003, 2011), it is currently unclear whether capacity limits influence auditory memory in a way that is consistent with visual STM. Most infant visual STM tasks involve a set of objects arrayed in space and presented simultaneously (e.g., Ross-Sheehy et al., 2003). Although this works well for studying capacity effects in the visual domain, it is not readily adaptable to the study of auditory STM, primarily because there is a limit on the number of distinct spatial locations that can be perceived simultaneously in the auditory domain. This difficulty is exacerbated by infants' poor auditory spatial localization abilities, which do not approach adult levels until children are at least 18 months of age (Clifton, 1992; Litovsky, 1997; Morrongiello, 1988).

Ross-Sheehy (2006) created a variant of the visual STM task that is more readily adaptable to the acoustic dimension. In this task, infants were presented with streams of colored squares, presented *sequentially* for 300 ms each, followed by a blank 600-ms retention interval. This sequence repeated over and over to create 20-s streams composed of colored squares that either changed color at every onset (e.g., red–blue, red–green, yellow–green) or stayed the same (e.g., yellow–blue, yellow–blue, yellow–blue) (see Fig. 1). Results from this task demonstrate that 10-month-olds, but not 5-month-olds, are able to encode sets of sequentially presented colored squares into visual STM, resulting in a robust preference for the changing stream (Ross-Sheehy, 2006). Thus, by 10 months, infants are able to encode items presented sequentially in time and retain that memory across a brief delay. Based on these findings, we developed an analogous auditory STM task by presenting sequences of sounds in the context of the infant head-turning procedure. This design allowed us to examine capacity limits in the number of *individual* items held in STM and also capacity limits with respect to sequence *duration.* Examining both of these features in the same study is ideal because work with adults indicates that limitations imposed by set size and duration may independently influence capacity (Cowan, Wood, Nugent, & Treisman, 1997). This makes it nearly impossible to identify the real source of capacity limitation when using typical verbal stimuli because most confound complexity (i.e., number of syllables) with duration (i.e., word length). Thus, non-verbal stimuli may be ideal for teasing apart the relative contribution of set size and set duration to working memory performance, and to our knowledge this is the first study to examine this in infants.

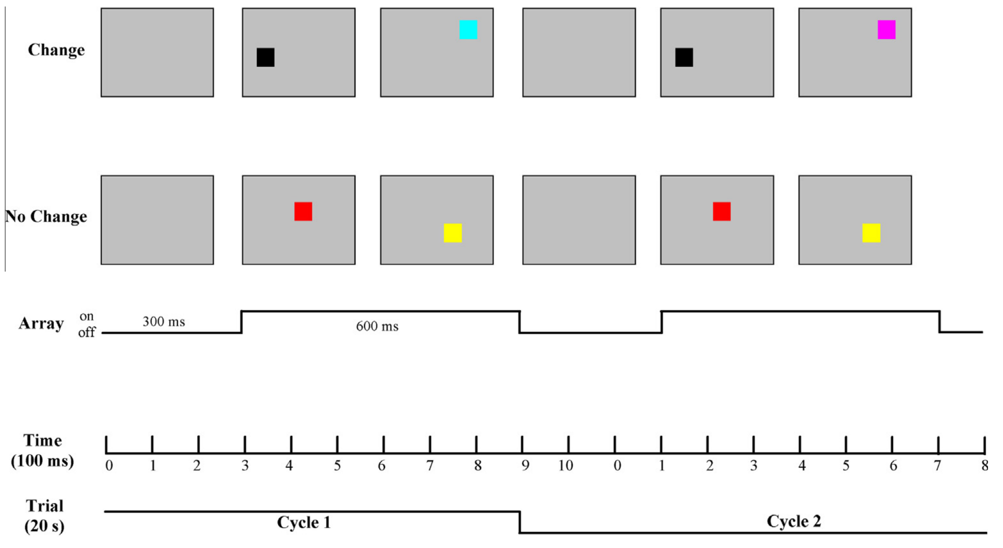

Fig. 1. Example of visual set size 2 streams (Varying and Non-varying) from Ross-Sheehy (2006).

The following three experiments demonstrate the effectiveness of this innovative new procedure for testing auditory STM and begin to disambiguate the relative contributions of stream duration and set size. Together, these studies establish that by 10 months infants can encode and remember "sets" of auditory items presented over time, just as they do in the visual modality, and that infant auditory STM capacity is limited with respect to duration of stimulus sequences and possibly the number of individual elements in a sequence.

Experiment 1

The purpose of Experiment 1 was to assess auditory STM using a procedure designed to isolate non-language-based STM systems. By examining memory for streams of sounds of varying complexity (2- or 4-instrument sequences), we can begin to identify typical non-verbal STM abilities. This experiment used a modified change detection paradigm and is modeled after tasks examining infant visual STM (Oakes et al., 2006, 2009, 2011; Ross-Sheehy et al., 2003, 2011). However, rather than colored squares, here we presented infants with sequences of notes created using of either 2 or 4 unique software instruments, followed by silent retention intervals. Just as in the visual task, these instrumental sequences were repeated over and over to create streams that were 20.4 s in length. Because these notes were presented sequentially, it was important to maximize discriminability by allowing dimensions such as timbre, attack, decay, and other spectral properties to vary across individual notes, just as properties such as hue luminance, saturation, and contrast vary across visual analogs of this task (e.g., Ross-Sheehy, 2006). Absolute pitch, however, was held constant from note to note to prevent the perception of melody, a form of perceptual "chunking" that occurs when a sequence of individual tones is perceived instead as a coherent pattern. Prior work has demonstrated that infants can readily distinguish these types of timbre differences among instruments (Trainor, Wu, & Tsang, 2004; Trehub, Endman, & Thorpe, 1990), and other studies have demonstrated infants' ability to use cues such as spectral slope and envelope, important components of timbre (Clarkson, Clifton, & Perris, 1988; Tsang & Trainor, 2002). We tested infants between 10 and 11 months because infants younger than this age showed no evidence of visual STM when items were presented sequentially as in the current task (Ross-Sheehy, 2006).

Streams were created, by stringing together these 2- and 4-note sequences, one after the other, separated by 500-ms retention intervals. These streams either stayed the same for every repetition (e.g., for 2-instrument sequences: flute–cello, flute–cello, flute–cello; for 4-instrument sequences: sax–cello–harp–piano, sax–cello–harp–piano, sax–cello–harp–piano) or changed by 1 instrument on each repetition (e.g., for 2-note sequences: piano–sax, piano–violin, harp–violin; for 4-note sequences: bass–strings–harp–sax, bass–strings–piano–sax, flute–strings–piano–sax). As is typical for change detection paradigms, we expected that infants would listen longer to the Varying sequences than to the Constant ones, but only when they could encode the entire 2- or 4-instrument sequence into STM, hold onto that memory across the 500-ms retention interval, compare the remembered sequence with the subsequent sequence, and detect the change if one is present. Although previous work indicates that by 6 months infants can encode and remember a single sound for up to 2.5 s (Plantinga & Trainor, 2008), it is currently unclear whether infants can encode more than a single sound into STM. Indeed, although both children and adults demonstrate strong memory for auditory verbal stimuli (e.g., words, syllables) that lasts for at least 1 s (Cowan, Nugent, Elliott, & Saults, 2000), this memory appears to be limited to the last item in the series. If infants cannot encode *all* of the instruments in a given sequence, then every instrument will sound equally new and listening preferences will drop to chance. Moreover, by varying both the number of notes in a sequence and the duration of each note in a sequence, it will be possible to probe the relative importance of complexity (i.e., set size) and duration (i.e., note/sequence length) in infant STM performance.

Method

Participants

Participants were 16 healthy, full-term infants (8 male and 8 female) aged 10.5 months (M_{age} = 45.2 weeks, SD = 2.1, range = 41.2–50.3), all of whom came from predominately English-speaking homes. An additional 2 infants were not included in the analyses due to experimenter error (n = 1) or excessive sleepiness (n = 1). Of the 16 infants, 10 were Caucasian, 2 were Asian, 1 was African American, 2 were Native American, and 1 was Hispanic. Two of the infants' mothers had graduated high school, 3 had some college experience, 3 had a 4-year college degree, 6 had a master's degree, and 2 had a doctoral degree.

Stimuli

A Macintosh G4 and the application GarageBand (Apple) were used to create a set of highly realistic instrumental sounds while controlling for properties such as duration and absolute pitch. We selected 8 instruments to maximize acoustic distinctiveness for short note durations (orchestral strings, alto sax, grand piano, pop flute, whirly, church bell, bondi breath, and tight synth bass), and all samples were created using C_5 (i.e., "C" note one octave above "middle C" on a standard 88-key piano keyboard). Notes for Experiment 1 were edited to be exactly 350 ms in duration. These individual instruments were then combined into sequences followed by a brief retention interval. Based on previous infant visual STM work (Ross-Sheehy, 2006; Ross-Sheehy et al., 2003), we conservatively selected 2- and 4-instrument sequences for this first study, producing sequences that in total duration were 700 ms for the 2-instrument sequence (350 ms for each note $\times$ 2 notes in a sequence), and 1400 ms for the 4-instrument sequence (350 ms for each note $\times$ 4 notes in a sequence). Stimulus *streams* were created by combining multiple iterations of each sequence type over and over for 20.4 s, with the provision that each instrument occurred equally often across streams. Half of these streams were composed of 4-instrument sequences, each separated by a 500-ms retention interval; the other half were composed of 2-instrument sequences, each separated by a 500-ms retention interval. Note that the use of a 500-ms memory interval ensures that we were testing STM and not *sensory persistence* given that adult auditory sensory memory persists for only approximately 250 ms (Cowan, 1984). Thus, we can be confident that a significant preference for the Varying stream does in fact reflect STM.

Variability of the streams was also manipulated. For half of the streams 2- and 4-instrument sequences simply repeated over and over (Constant), and for the other half one randomly chosen instrument was changed every time the sequence repeated (Varying). The member of the sequence to be changed and the instrument it was changed to were both selected randomly, with the provisions that the changing instrument needed to be a new instrument and no instrument could be repeated within a given sequence. This resulted in four stream types: 2-note Constant, 2-note Varying, 4-note Constant, and 4-note Varying.

Procedure

A variant of the head-turn preference procedure (Kemler Nelson et al., 1995) was used to assess auditory memory. This and all subsequent experiments were carried out in a 4 × 6-foot, three-sided test booth constructed from white pegboard panels. Each infant was seated on the caregiver's lap in the test booth. A yellow light located in the center of the front panel was used to attract the child's attention, whereas a video camera (with a lens coming through a hole in that same front panel) provided video footage of each test session. Each side wall contained a red light in the center of the panel, marking the location of an occluded loudspeaker (NHT Super One, with a frequency response from 57 Hz to 25 kHz ± 3 dB) that was secured to the back of the panel. The child was seated midway between the two lights, approximately 3 feet from each speaker.

At the start of each trial, a light in the center panel began to flash, attracting the infant's attention front and center. Once the infant looked to the flashing light, an experimenter pressed a button on the button box, the center light was extinguished, and a light on one of the two sides of the booth began to flash. Once the infant turned toward that light, the sound for the trial began to play and continued until the infant looked away for a consecutive 2 s or the sound file ended (20.4 s), whichever came first.

As is standard for infant head-turning techniques, the experiment began with a practice phase intended solely to familiarize infants with the task (i.e., to teach them that looking at the lights resulted in sounds being played). During this phase, infants heard 4 trials with classical music, which played only when children looked at the light adjacent to the sound source, for a maximum of 14.9 s. Over the course of this familiarization, infants learned the contingency between looking and hearing and tuned their responses appropriately (e.g., looking to the light to produce the sound, looking away when they became disinterested). Thus, *looking* during the test phase of this paradigm is used as a measure of *listening*. During the test phase, infants heard the 16 test trials arranged in blocks, such that each block contained one of each trial type: 2-instrument Varying, 2-instrument Constant, 4-instrument Varying, and 4-instrument Constant. Side of the booth for presentation was random, with the

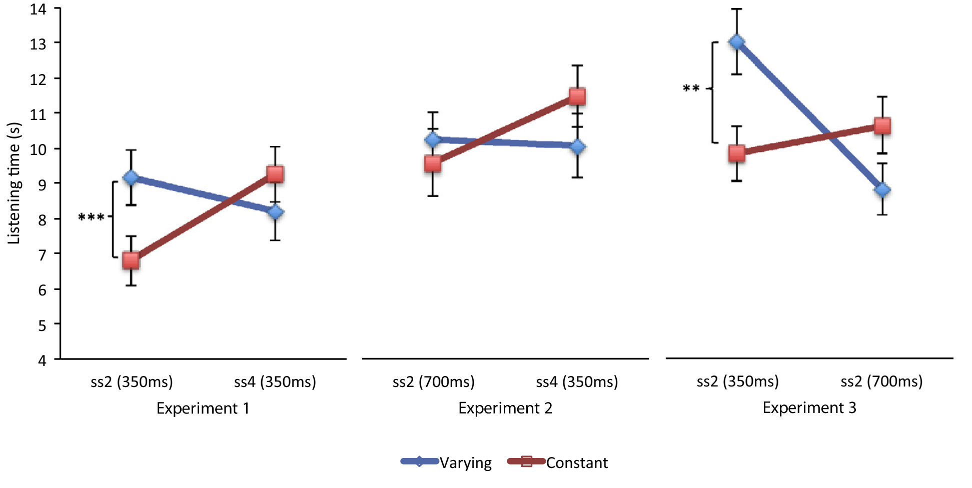

Fig. 2. Listening time (in seconds) to Varying and Constant streams for Experiment 1 (left panel), Experiment 2 (middle panel), and Experiment 3 (right panel). Labels denote set size (ss2 and ss4) and duration of each instrument in the series (350 ms and 700 ms). For Experiment 1, instrument duration was held constant (350 ms), whereas set size (ss2 vs. ss4) and total duration (700 ms vs. 1400 ms) varied. For Experiment 2, total duration was held constant (1400 ms), whereas instrument duration (350 ms vs. 700 ms) and set size (ss2 vs. ss4) varied. For Experiment 3, set size was held constant (ss2), whereas instrument duration (350 ms vs. 700 ms) and total duration (700 ms vs. 1400 ms) varied. Significant simple main effects are indicated with $^{***}p < .001$ and $^{**}p < .01$, and error bars represent ±1 standard error.

one exception that no more than 3 trials occurred in a row on the same side of the booth. Within those constraints, eight different random orders of trials were created, and each order was used for a minimum of 1 participant, and no more than 3 participants, in a given sample.

The experimenter pressed buttons on a computer-controlled response box to indicate when the infant looked toward or away from the flashing light (the source of the sound). The total time spent looking on each trial was recorded on the computer; any time the infant spent looking away from the light (whether 2 s or less) was not included in the total duration of the child's looking time. The experimenter and caregiver wore Peltor aviation headphones playing masking music in order to avoid biasing the child's behavior or the coding of that behavior.

Results

A 2 (Sequence Length: 2-instrument vs. 4-instrument) $\times$ 2 (Sequence Type: Varying vs. Constant) repeated measures analysis of variance (ANOVA) was conducted to examine the effect of sequence length and sequence type on listening durations. This analysis revealed a marginal main effect of sequence type, $F(1,15) = 3.27$, $p = .091$, $\eta_p^2 = .18$, which was subsumed under a significant sequence length by sequence type interaction, $F(1,15) = 15.37$, $p = .000$, $\eta_p^2 = .51$. Importantly, the main effect for sequence length was not significant, suggesting that infant listening is not simply driven by the length (i.e., complexity) of a given sequence, $F(1,15) = 2.45$, $p = .138$ (Fig. 2, left panel).

To follow up this significant interaction, simple main effect tests were conducted comparing listening duration for the Constant and Varying streams. To control for Type I error across the two simple main effects, we set alpha for each at .025. This analysis revealed that infants listened significantly longer to the Varying streams than to the Constant streams for 2-instrument sequences, $F(1,15) = 24.90$, $p = .000$, $\eta_p^2 = .62$, but not for the 4-instrument sequences, $F(1,15) = 2.60$, $p = .128$, $\eta_p^2 = .15$. Thus, it appears that infants can detect a changing stimulus in streams composed of 2-instrument sequences, but there is no evidence of change detection in streams composed of 4-instrument sequences.

Discussion

These results provide the first evidence that by 10 months infants can rapidly encode sequences of naturalistic sounds into auditory STM. In many respects, this is remarkable given that our instrument sequences varied only in the spectral properties/attack properties of the sound (e.g., the instrument) and not in absolute pitch. Nonetheless, infant auditory STM capacity appears to be limited to streams composed of at least 2 instruments but not 4 instruments. However, the streams used in Experiment 1 differed not only in the number of instruments per sequence but also in the *total duration* of each sequence. That is, because all of the notes were 350 ms, the 2-instrument sequence had a total duration of 700 ms, whereas the 4-instrument sequence had a total duration of 1400 ms. It is possible that the total duration of the 4-instrument stream rather than set size per se, may have driven our capacity effect. Work with adults has demonstrated an interesting dissociation between short (<250 ms) and long ($\sim$10 s) auditory stores (Cowan, 1984; Loveless, Levänen, Jousmäki, Sams, & Hari, 1996) that may have implications for the current task. If short duration auditory events persist for even just a few hundred milliseconds, then infants could theoretically detect the acoustic differences between Instrument 1 and Instrument 2 even with no STM capacity. However, this simple discrimination ability could not account for our significant preference for the Varying stream of sounds given that infants must compare each subsequent sequence in its entirety in order to notice that one of the instruments has changed. This process of comparison requires encoding whole sequences of sounds (e.g., cello–flute; 700 ms), maintaining that sequence in memory across the interstimulus interval (ISI) (500 ms), and encoding the entire subsequent sequence (e.g., cello–piano; 700 ms) in order to detect that one of them has changed. For Experiment 1, this whole cycle requires maintaining a durable memory, in the face of interference, for 1900 ms in the set size 2 (ss2) conditions and for 3300 ms in the set size 4 (ss4) conditions. Clearly, even our set size 2 streams require some form of working memory. However, we cannot determine, based on the results of Experiment 1 alone, whether infants succeeded for 2-instrument sequences, but not 4-instrument sequences, due to constraints on the *number* of individual instruments that could be maintained in STM (i.e., capacity) or constraints on the *duration* of each instrument or instrument sequence that infants can encode into memory. To begin to untangle these alternative explanations, we held one aspect of duration constant (sequence duration) to examine the effect of set size (2- or 4-instrument sequences).

Experiment 2

If infants' auditory STM capacity is limited primarily by the *number* of items to be stored in memory (e.g., Zhang & Luck, 2011), then performance should vary as a function of the number of instruments in a sequence (i.e., set size) regardless of sequence duration. If, however, STM capacity is limited primarily by the overall *duration* of the instrument sequence, then infants should be able to remember a greater number of shorter duration instruments than longer duration ones. Similar effects have been documented in verbal memory, for example, with increased memory performance for lists composed of short-duration words relative to long-duration words (Baddeley, Thomson, & Buchanan, 1975; but see Cowan et al., 1997). Although these results are interesting, caution should be exercised when extrapolating between verbal and non-verbal working memory tasks because previous work suggests that these memory stores are indeed dissociable (Li et al., 2013; Schulze & Tillmann, 2013). There are two possible ways of examining this issue with our stimuli. One approach would be to test whether infants could successfully store a 4-instrument sequence when each note was half of the duration used in Experiment 2, such that the 4-instrument sequence had the same overall duration as the 2-instrument sequence in the prior experiment. However, the instruments selected in Experiment 1 differed, in part, on the basis of their attack; as these notes become shorter, their timbre differences became less noticeable, making it harder to hear the distinction between Varying and Constant trials. For this reason, we instead selected the opposite approach; we examined whether infants would still be able to recognize a 2-instrument sequence when each note was twice as long in duration, such that the 2-instrument sequence tested here had the same overall duration as the 4-instrument sequence from Experiment 1. If infants can store at least 2 instruments in auditory STM regardless of their duration (within a reasonable range), then infants should once again listen longer to Varying streams than to Constant streams even with these longer notes. If, however, the difference in performance we observed in Experiment 1 reflected, in part, differences in the duration of 2-instrument versus 4-instrument sequences, then infants should fail to show a preference for 2-instrument Varying streams when the individual sequences are lengthened in duration to equal the 4-instrument sequence.

Method

Participants

Participants were 16 healthy, full-term infants (10 male and 6 female) aged 10.5 months (M_{age} = 44.4 weeks, *SD* = 1.8, range = 41.6–47.1), all of whom came from predominately English-speaking homes. All of the infants' mothers had at least some college education; of the 16 mothers, 1 had 2 years of college, 7 had a bachelor's degree, 7 had a master's degree, and 1 had a doctoral-level degree. Of the 16 infants, 10 were Caucasian, 2 were Asian, 1 was African American, 1 was Pacific Islander, and 2 were Hispanic. An additional 2 infants were tested but excluded from the analysis due to parental report of ear infection.

Stimuli

Stimuli were similar to those in Experiment 1, with the exception that both 2- and 4-instrument sequences were equated for total duration (1400 ms). Thus, for 2-instrument sequences each note was 700 ms, and for 4-instrument sequences each note was 350 ms.

Procedure

The procedure was identical to that in Experiment 1.

Results

A 2 (Sequence Length: 2-instrument vs. 4-instrument) × 2 (Sequence Type: Varying vs. Constant) repeated measures ANOVA conducted on infant listening duration revealed no significant main effect of either sequence type, $F(1,15) = 2.33$, $p = .682$, or sequence length, $F(1,15) = 2.37$, $p = .145$, and no significant interaction, $F(1,15) = 3.07$, $p = .100$ (Fig. 2, center panel). No other analyses were conducted.

Discussion

This result is interesting and suggests that performance in Experiment 1 may have been driven primarily by the differing durations of the 2- and 4-instrument sequences rather than the number of items (set size) in the sequence. However, it is currently unclear whether duration and set size interact to influence capacity or whether duration is the primary constraint on change detection. Moreover, it is possible that infants in Experiment 2 were able to discern the 2- and 4-instrument sequences but failed to show a preference for some other reason. Thus, to more directly test the influence of duration on Varying preferences, in Experiment 3 we manipulated the individual duration of each instrument (and, consequently, total sequence duration) while holding set size constant at 2-instrument sequences. This provides an important replication of our significant effects from Experiment 1 (ss2, 350 ms) and our non-significant effects from Experiment 2 (ss2, 700 ms) and provides a critical test of the effect of duration on preference for Varying streams.

Experiment 3

Results from Experiment 1 suggested that infants could remember 2-instrument sequences, but not 4-instrument sequences, when the notes were each 350 ms long, and results from Experiment 2 suggested total duration to be a critical factor in auditory STM tasks. Together, these findings imply that infants can store at least 2 unique instruments, but only for a total duration of less than 1400 ms. However, this claim is tenuous because it is based in part on a null result (Experiment 2). In addition, it is possible that preference for 2-instrument Varying sequences, but not 4-instrument Varying sequences, found in Experiment 1 was driven not by set size per se but rather by the greater *proportional change* found in the 2-instrument streams compared with the 4-instrument streams. That is, for each 2-instrument Constant sequence, the *net rate of change* was .50 (1 change every 2 instruments), whereas for the 4-instrument Constant sequence, the net rate of change was only .25 (1 change every 4 notes). Thus, as a more stringent test of duration effects on STM capacity, we compared infants' performance for 2-instrument sequences but varied the duration of the individual notes comprising each sequence to be either 350 ms long (as in Experiment 1) or 700 ms long (as in Experiment 2). If infants can encode and remember notes that are 700 ms in duration but not notes that are 1400 ms in duration, then we would expect a robust Varying preference for short sequences but not for longer ones. If, however, total sequence duration was not the primary cause of our null result in Experiment 2, then infants should listen equally to both the shorter and longer sequences. Thus, Experiment 3 provided a critical test of the effects of sequence duration within known set capacity limits (i.e., 2-instrument sequences). Finally, Experiment 3 also controlled for the proportion change hypothesis by holding rate of change constant at .50 for both the longer and shorter sequences.

Method

Participants

Participants were 16 healthy, full-term infants (7 male and 9 female) aged 10.5 months (M_{age} = 45.9 weeks, SD = 1.8, range = 43.1–48.1), all of whom came from predominately English-speaking homes. All participants were Caucasian except for 1 child who was Asian/African American. All of the other infants' mothers had at least some college-level education; of the 16 mothers, 4 had a bachelor's degree, 5 had a master's degree, and 2 had a doctoral-level degree. An additional 9 infants were tested but excluded from the analysis due to prematurity ($n = 2$), crying/fussiness ($n = 5$), equipment difficulties ($n = 1$), or having a non-English-speaking household ($n = 1$).

Stimuli

Stimuli for Experiment 3 were drawn from the same pool of 8 instruments and were all composed of 2-instrument sequences. The duration of each note was manipulated, such that notes were either 350 ms (700-ms sequence) or 700 ms (1400-ms sequence). Given the longer length of the 700-ms notes, we increased the ISI for both sequences slightly from 500 to 700 ms to better delineate the sequences from each other. This resulted in slightly longer trials overall. To explore the effect of this manipulation on total listening, we conducted an independent sample *t* test comparing total listening duration for Experiment 3 with total listening duration for Experiment 2. Results revealed no significant difference, $t(30) = -0.281$, $p = .780$, indicating that our slightly increased ISI did not influence overall attention or interest.

Procedure

The procedure was identical to that in Experiments 1 and 2.

Results

We conducted a 2 (Sequence Duration: 1400 ms vs. 700 ms) $\times$ 2 (Sequence Type: Varying vs. Constant) repeated measures ANOVA on infant listening time. Results of this analysis revealed a marginally significant main effect of sequence duration, $F(1,15) = 4.51$, $p = .051$, $\eta_p^2 = .23$ (Fig. 2, right panel). However, this main effect was once again subsumed under a significant sequence duration by sequence type interaction, $F(1,15) = 12.05$, $p = .003$, $\eta_p^2 = .45$, suggesting that infant memory for 2-instrument sequences was driven primarily by sequence duration, with infants showing a robust Varying preference for 700-ms sequence streams but not for 1400-ms sequence streams. There was no main effect of sequence type, $F(1,15) = 0.84$, $p = .373$.

To follow up this significant interaction, simple main effect tests were conducted comparing listening duration for the Constant and Varying streams. To control for Type I error across the two simple main effects, we again set alpha for each at .025. As predicted, this analysis revealed that infants listened significantly longer to the Varying streams than to the Constant streams for the shorter 700-ms sequences, $F(1,15) = 10.44$, $p = .006$, $\eta_p^2 = .41$, but not for the longer 1400-ms sequences, $F(1,15) = 2.72$, $p = .120$, $\eta_p^2 = .15$.

Discussion

The results from Experiment 3 demonstrate clear STM capacity effects for 2-instrument auditory sequences that did not exceed 700 ms in duration. That is, infants were able to encode and remember sequences made up of individual distinct instruments, but only when those sequences did not exceed 700 ms in total duration. Moreover, this finding replicates our null result from Experiment 2 and further suggests that the pattern of effects found in Experiment 1 was not simply caused by varying rates of change between the 2-instrument and 4-instrument streams.

General discussion

Working memory and STM are notoriously difficult to test in infants. We have presented here results from three experiments examining infants' auditory STM capacity for non-linguistic sequences of instruments using a novel approach for the study of infant auditory STM. Although logistical realities make it almost impossible to directly estimate STM capacity in preverbal infants, this task measures *capacity effects* by examining changes in discrimination of streams with higher or lower STM capacity loads (e.g., 2 or 4 instruments, 700- or 1400-ms stream duration). Taken together, results from these three experiments demonstrate that 10-month-olds have auditory STM for non-linguistic sounds and that, like STM in the visual modality, auditory STM shows clear capacity effects.

Specifically, our results demonstrate clear capacity effects with respect to the total duration of a sequence; infants listened longer to the Varying streams than to the Constant ones, but only when sequence durations were less than 1400 ms (Experiments 1 and 3). In addition, our results suggest a possible second capacity effect for the number of distinct items an infant can hold in auditory STM, with infants successfully detecting the Varying sequence for 2-instrument streams but not for 4-instrument streams (Experiment 1). Although we were unable to directly probe the number of distinct instruments an infant can hold in STM due to stimulus limitations, it is certainly possible that 10-month-olds can remember more than 2 instruments provided that they are sufficiently distinct and fit within the duration capacity limits identified for the first time here. Although limitations of our current stimulus set preclude us from testing 3-instrument sequences, results presented here suggest that *duration* capacity effects, rather than *set size* capacity effects, may be the real bottleneck when using more natural sound streams such as we did here. Future work will be aimed at addressing this question precisely. Nonetheless, this is the first study to examine STM for auditory object identity (set size effects) and duration (sequence duration) in infants and, thus, sets the stage for further explorations of how this capacity-limited system might change with development.

Note that the current study explored capacity limitations only for non-linguistic stimuli. It remains unclear whether such findings would extend to verbal stimuli. As noted previously, memory for verbal and nonverbal auditory stimuli are dissociable in adults, and it is possible that linguistic stimuli may have different capacity limitations for young infants, either via a specialized phonological/verbal memory store or via more sophisticated chunking mechanisms that influence what constitutes a "unit" for linguistic stimuli or due to differences in neural circuitry. There is some evidence for functionally and anatomically distinct cortical networks for phonological and non-linguistic working memory (Stevens, 2004). However, despite evidence that the two domains are dissociable, they may still be at least partially interdependent. The testing procedure introduced here to examine the capacity limits for musical instruments could easily be extended to explore capacity limits for speech syllables, thereby allowing for a direct comparison between linguistic and non-linguistic auditory STM. This promising work is currently being conducted in our lab.

If the findings of limited capacity in infant auditory STM were to extend to phonological STM, it would have implications for a wide range of theories of verbal language. In particular, such limited capacity could influence the ability to detect changes in the streams of morphemes and phonemes that make up speech. Interestingly, infants' typical acoustical environments seem to be well-tuned to scaffold infants' STM capacities. For example, parents speak quite differently to young children than they do to adults, and the input that infants receive seems to be specialized for their particular language and/or attentional needs. First, utterances to young infants are often quite short, with parents frequently producing words in isolation or in short phrases and incomplete sentences (Brent & Siskind, 2001). These brief utterances may be more likely to fit within auditory STM limits identified here. Indeed, children's vocabulary development has been reported to correlate with the proportion of time their parents produce words in isolation (Brent & Siskind, 2001). Second, parents' utterances do not increase in mean length until after children reach 24 months of age (see Phillips, 1973, and Soderstrom, 2007, for reviews; Stern, Spieker, Barnett, & MacKain, 1983); it would be worth investigating whether such increases in length co-occur with increases in children's STM.

Along these lines, (Newport, 1990; but see Rohde & Plaut, 2003) suggested that limits on children's STM may actually be beneficial for learning language. In her "less is more" hypothesis, she argued that young children cannot store as many components of an utterance as adult listeners, and this limitation forced them to a more local syntactic analysis of the input stream, which may have indirectly scaffolded language learning. Although Newport made no claims as to whether STM capacity increases with development, or whether adults are simply better able to make use of their STM, our finding of limited auditory STM capacity, with respect to both the number of items an infant can remember and the duration they can remember those items, fits nicely with this theory. However, although infant-directed utterances frequently consist of only two or three syllables or words (e.g., "peek-a-boo!", "pretty baby!"), they are generally spoken more slowly and may still exceed the meager 1 s worth of information that infants can hold in STM. It is worth noting that studies to date investigating infant-directed speech have typically measured parental speech in terms of the number of words or morphemes per utterance and not the actual temporal duration of typical utterances. Thus, it is not clear what proportion of infant-directed utterances are likely to fit within the capacity limits described here. Individual words, however, are quite likely to fit within this time frame given that most words that children learn early, at least in English, are mono- or bisyllabic (Fenson et al., 1994).

In addition, it is possible that infants need only to encode a subset of acoustic information to begin the process of word learning. For example, Saffran's work examining statistical learning in infants demonstrates that infants can quickly learn "words" based solely on the transitional probabilities of neighboring syllables (e.g., Saffran, Aslin, & Newport, 1996). This finding was also replicated when spoken "words" were replaced with tone "words" (Saffran, Johnson, Aslin, & Newport, 1999). Because detecting transitional probabilities requires infants to remember at least two syllables, our work suggests that syllable duration may be a critical parameter in statistical learning paradigms. Interestingly, both the 222-ms syllables used for speech streams (Saffran et al., 1996) and the 333-ms syllables used for tone streams (Saffran et al., 1999) were short enough to fit within duration capacity limits suggested by our work. Of course, parents also help infants to compensate for memory limitations by putting important target words at either the beginning or end of an utterance (Aslin, 1993) and by producing words in isolation (Brent & Siskind, 2001). Examining the limits of children's STM in combination with the input children receive may lead to new insights about how the process of language development occurs.

In summary, we have presented here the results from three novel experiments examining infant auditory STM for non-linguistic sounds. Based on the findings presented, we conclude that by 10 months infants can encode at least 2 unique naturalistic instruments in STM and can remember at least 700 ms worth of information but less than 1400 ms (i.e., ~1 s worth of information). To our knowledge, this research is the first to successfully examine STM for non-linguistic stimuli in infants, providing an important framework on which to base future research efforts, including research on capacity for object identity and item duration, relation to capacity for linguistic stimuli, and relation to later cognitive development. Finally, this is the first work examining auditory STM in a way that is similar to visual STM, allowing us to begin to address larger theoretical issues of development across multiple domains.

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