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Numbers in Short-Term Memory Bias Auditory Spatial Perception

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The cognitive penetration literature suggests that top-down knowledge influences perception, but whether such influences exist is controversial. We tested for top-down influences on perception by loading short-term memory with digits and then had participants make perceptual judgments to index spatial hearing. Memory of spatial number codes were predicted to bias spatial judgments to the left for small digits and rightward for larger digits. Participants encoded one or more digits and then made spatial judgments in either spatial hearing or dichotic listening tasks. Results across five experiments supported the predicted spatial biases. Digits had to be deliberately encoded, and at least two were needed to be memorized before a small number left-right bias in dichotic listening was evident. In dichotic listening, smaller numbers in memory also promoted more intrusions, and a mix of small and large numbers enhanced the right ear advantage. Results suggest that long-term knowledge about number magnitude imparts a top-down bias on auditory spatial perception.

Public Significance Statement

Perceptual systems represent information sampled from the environment. It is important for such systems to accurately preserve this information, which may interact with other cognitive functions such as attention, memory, executive functions, decision making, and action. Prior work suggests that information from other cognitive systems might infiltrate perception ("cognitive penetration"), leading to subtle perceptual biases. However, there are multiple conceptual and methodological challenges that argue against the existence of cognitive penetration. This study took a different approach by experimentally manipulating the contents of short-term memory while participants performed auditory spatial perception tasks. We found that the magnitude of numerical information in short-term memory has a systematic influence on auditory spatial perception.

Keywords: cognitive penetration, dichotic listening, right-ear advantage, spatial hearing, working memory

One of the most basic questions in cognitive science is how perceptual data interface with "higher-level" cognitive systems such as attention, language, memory, executive functions, decision making, and action. The feedforward contribution of perception to these other systems is obvious; perception supplies information that is attended, recognized, remembered, considered, and perhaps acted upon. Here we consider the possibility that the interplay between perception and other cognitive systems is to some degree bidirectional. If correct, this would mean that perception can be systematically affected by the contents of these other systems during stimulus processing. Higher cognition would thus be able to leave its mark on perception.

The issue of whether higher-level cognition influences perception is termed "cognitive penetrability," or the converse term of "encapsulation," and has been extensively discussed in the cognitive science and philosophy literatures (e.g., Bruner & Goodman, 1947; Pylyshyn, 1999). On functional grounds, in the healthy brain good encapsulation is necessary to accurately convey sensory data for use by other cognitive systems. Nonetheless, hallucinations attributable to brain disease provide an existence proof for extreme cognitive penetration, and such failures of encapsulation are characteristic of schizophrenia, Lewy body dementia, Charles Bonnet syndrome, and auditory hallucinosis, among others (Griffiths, 2000; Powers et al., 2016). With respect to normative brain and cognitive function there are a wide range of views, from no cognitive penetration (Firestone & Scholl, 2016) to having cognition strongly bias perception, particularly in the realms of emotion and embodied cognition (Balcetis, 2016; Collins & Olson, 2014).

In the present study we focus on the more modest proposition that in healthy individuals higher cognitive systems can induce small, but systematic, top-down biases that affect basic aspects of perception. By stating "basic aspects," we are referring to the

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perception of elemental sensory features such as form, color, pitch, loudness, and location. As with other important laboratory behavioral phenomena, such effects on reaction times that differ by tens of milliseconds, the hypothesized perceptual biases can go unnoticed in everyday life. Testing for evidence of perceptual biases by higher-level cognitive systems is important because the findings may provide clues about how different cognitive systems interact with each other.

Impact of Short-Term Memory Load on Performance

One strategy to test relations between perception and higher cognitive systems is to use short-term memory (STM) as a model higher cognitive system. An advantage of focusing on STM is that the type and amount of information in STM is under experimental control.[1] Thus, perception can then be examined as a function of the content in STM at the time that stimuli are delivered for perceptual judgment. When measures of performance are examined, such as reaction time (RT) or accuracy, the contents of STM are known to have a strong influence. The Stroop effect provides one example. When participants respond on the basis of font color, reaction times slow down when the meaning of color words conflicts with font color (Macleod, 1991; Stroop, 1935). However, the Stroop effect is also observed when participants judge color patches while color words are retained in STM (Kiyonaga & Egner, 2014). Incidental information about a memorized stimulus, such as its location when memorizing faces, can also influence performance, in this case by speeding-up RT to probes (Downing, 2000). A similar enhancement of RT is seen when spatial information is explicitly maintained in STM (Awh et al., 2000). Words with conceptual spatial associations can also systematically influence response speed to subsequent targets (Gozli et al., 2013; Sun et al., 2015). Most previous studies are in the visual modality, but in the auditory modality STM load also influences performance; however, the results have been mixed (Berti & Schroger, 2003; Dalton et al., 2009; Golob, Winston, et al., 2017). Crossmodal effects have also been observed, for example visual STM load can affect the accuracy of speech cue discrimination (Mattys & Wiget, 2011; Mitterer & Mattys, 2017). Finally, recent studies have probed in detail whether the effects of memory load on performance are general, or instead depend on the relation between the type of information in memory relative to what is needed to do the task (De Fockert, 2013; Gil-Gómez de Liaño et al., 2016; Golob, Winston, et al., 2017; Kim et al., 2005; Logan, 1979; Olivers et al., 2011; Park et al., 2007; Woodman & Luck, 2004).

Distinction Between Performance and Perceptual Measures

The above studies show that information in STM has sway over performance measures such as RT and accuracy. One limitation of using such performance measures is that they do not directly inform us about *how* participants perceived the stimuli. That is, a participant's conscious experience does not typically map onto speed of output. For example, in Stroop tasks the reaction times to different colors are comparable and thus one cannot use RT to deduce which color was perceived on a given trial. Consequently, other methods are used to study the subjective aspects of perception. One common approach is to measure psychometric functions, which are derived by varying a stimulus parameter, such as intensity, and plotting parameter values against a dependent variable. The shape of the psychometric function is then examined relative to an independent variable of interest (Wichmann & Hill, 2001). Another approach is to have participants report which one of a small set of possible percepts was experienced. This is often done when a stimulus can be perceived in more than one way on separate presentations (termed "multistability"; Leopold & Logothetis, 1999), which includes dichotic listening (Hugdahl, 2003; Yurgil & Golob, 2010). The current study used both of these approaches (psychometric functions, dichotic listening) to examine whether the contents of STM can influence auditory perceptual experiences.

Associations Between Number Value and Space

A key consideration for any STM effects on perception is how the information in STM relates to the information in a perceptual system. Besides the memory item itself, information associated with an item in memory may also influence perception. For example, words are associated with other words in long-term memory, or a given word can have more than one meaning. These word associations are often abstract in nature, such as conceptual associations, rather than of perceptual features, and would perhaps be less likely to influence basic perception. On the other hand, asking participants to remember perceptual features has the potential to introduce experimental demand, because participants may intentionally or unintentionally respond based on what they think the experimenter wants.

In this study we capitalized on associations between numbers and space in an effort to use memory items with spatial associations that may influence perception, while also having more distant associations to avoid obvious experimental demand. The best-defined association between numbers and space is a mapping between the left-to-right sides of egocentric space and smaller-to-larger numbers (reviewed in Hubbard et al., 2005). Such an association is supported by convergent evidence from behavioral studies in healthy controls (Casarotti et al., 2007; Dehaene et al., 1993; Gevers et al., 2006; Ishihara et al., 2006; Moyer & Landauer, 1967; Restle, 1970; Song & Nakayama, 2008), patients with brain damage (Mayer et al., 1999), and neuroimaging methods (Piazza et al., 2007). We reasoned that if participants are making spatial perceptual judgments, subject demand is more likely to occur if participants are also asked to remember spatial locations, compared with remembering numbers. The largely implicit associations of space and number are also a way to probe the organization of STM, in this case using two qualitatively different types of representations (verbal/number, and spatial). Note that such associations can be explicit in people who have a number-space variant of synesthesia (Ward, 2013), but for most people the association is largely implicit.

[1] Working memory broadly consists of interactions among short-term memory, perceptual, attention, and long-term memory systems (Baddeley, 2012; Cowan, 1995). We make the common distinction between maintaining information over short periods of time (short-term memory) from both maintaining and manipulating information (working memory; Miyake & Shah, 1999). The two constructs are related but are nonetheless empirically distinct (Engle et al., 1999; Shelton et al., 2010).

Rationale of the Current Study

Some of our previous work showed that hearing a number had a lingering influence on sound localization, (Golob et al., 2016). These observations suggest some degree of cognitive penetrability for perceptual judgments of sound location, while also addressing some limitations noted in previous work (for critique see Firestone & Scholl, 2016). The limitations that were addressed included using perceptual measures rather than RT and lessening experimenter demand by using indirect spatial associations with number magnitude. Control of low-level stimulus features and attention was achieved by mixed designs, observing parametric effects of number magnitude on spatial hearing, testing in two different languages and two different response metrics. With the exception of using different languages, the present study also includes the above design features. One limitation that is not addressed is whether the locus of any number bias affects early perceptual processing and/or later decision stages (Montemayor & Haladjian, 2017). For the current study we set aside the issue of early versus later stages of perceptual processing, which in our view is better addressed using neurophysiological methods with precise temporal resolution (e.g., single-unit recordings, local field potentials, EEG/MEG measures, intracranial and transcranial stimulation).

The current study asked whether having numbers in STM can bias spatial judgments of nonnumeric stimuli, in a manner similar to what is observed for immediate spatial judgments of numeric stimuli. The main question was whether the previously observed number bias on auditory spatial perception arises during fleeting perceptual processes or, instead, can have a persistent bias when retained in STM. It is well established that precise sensory information is only briefly retained in echoic memory (several seconds) and is susceptible to interference by the next stimulus (Cowan, 1984). This raises the question of whether the precise representation of sensory features is necessary for number biases on spatial hearing. A complementary question is whether spatial biases are present when number information is delivered separately from spatial information, rather than together as an auditory object that has spatial and numeric dimensions. The results of Golob et al. (2016) suggest this is possible, but that study was limited on this point because STM retention was not formally assessed.

Lastly, previous experiments directly inferred spatial bias as a function of presenting individual sounds at different locations. The current study expands this line of inquiry by examining spatial biases in dichotic listening, in which two different consonant-vowels are presented concurrently, one to each ear. The most important difference between dichotic listening and location judgments is that dichotic sounds are perceived to originate at the interaural midline. Spatial bias in dichotic listening would be evident by differences in the likelihood of perceiving the sound delivered to the left versus right ear. Note that the approach of having numbers in memory while making dichotic judgments of consonant-vowels is distinct from previous studies that examined memory for dichotically-presented information itself (Kimura, 1961a; Penner et al., 2009).

In the current report five experiments tested whether number information in STM can bias spatial perception of other stimuli, using white noise and psychophysical methods (Experiments 1 and 2) and consonant vowels during dichotic listening (Experiments 3–5).

Experiment 1

Method

Participants

Sixteen young adult participants were tested in a sound booth (age 19.2 ± 1.9; M/F = 7/9; 16/16 right-handed). In prior work we examined spatial judgments when participants listened to individual digits (Golob, Lewald, et al., 2017) and found that the correlations between digit magnitude and the measure of spatial hearing used below were r = .93 (Experiment 2) and r = .54 (Experiment 3, no cue condition). Power analysis showed that either six or 25 participants would be needed for power = .80, $p < .05$, depending on whether the larger or smaller correlation was used as the expected effect size. To be conservative, as well as account for potentially smaller effects when digit information was in memory, the power analysis used the smaller effect. We planned to test 25 participants but given uncertainty in effect size also noted the results during data collection. Participants were screened by self-report for major psychiatric and neurological disorders, as well as substantial hearing impairments. Audiometric testing used an audiometer (.5–8.0 kHz); all participants were in the normal range, and none was excluded. Participants also filled out a handedness survey (Oldfield, 1971). The experiments in this report were performed in accordance with protocols approved by the Institutional Review Boards of University of Texas San Antonio and Tulane University.

Experimental Design

The purpose of Experiment 1 was to determine whether merely hearing a number shortly before a white noise target can bias judgments about the target's location. Participants were not asked to remember the number. A previous study using a similar approach found that digits biased target location judgments in the central-to-eccentric (e.g., medial-to-lateral) directions for smaller-to-larger digit values, respectively (Golob et al., 2016). The Golob et al. (2016) study examined lateral locations using a pointing task. Here locations near midline were tested using psychophysical methods. Comparing midline to lateral locations is worth doing because primate auditory cortical neurons have multiple types of spatial codes, including left-right and contralateral-ipsilateral axes, central-eccentric directions, and front versus rear space (Remington & Wang, 2018).

Auditory spatial judgments were quantified using psychometric functions defined by the method of constant stimuli. Target locations varied between ±12° to the left or right of midline, and a sigmoidal-shaped function is apparent when target location is plotted against the proportion of trials having a "right" side judgment. The point of subjective equality (PSE) is defined as the location were left/right judgments were equally likely, and was predicted to vary with number magnitude as when directly making left/right judgments of number stimuli (Golob, Lewald, et al., 2017). Smaller numbers were expected to expand the left side of perceived space and move the PSE to the right, and the opposite pattern was expected for larger numbers. In the absence of any bias the PSE would correspond to the midline (0° straight ahead), which was expected for intermediate numbers. On ten percent of the trials the number was replaced by an amplitude modulated white noise, which served as a control stimulus that did not contain numeric information.

Materials and Stimuli

Stimuli were presented using insert earphones (Etymotic Research, Elk Grove Village, IL) at ∼60 dB nHL. English digits from one through nine, spoken by an adult male, were recorded at a sampling rate of 44.1 kHz (mean duration = 440 ms; range = 290–570 ms; ∼60 dB nHL). An amplitude modulated white noise stimulus (5 ms rise/fall time, 100–10,000 Hz; 25 Hz modulation at 90% depth; 440 ms duration; ∼60 dB nHL) was used as a nonnumeric control. Amplitude modulation was used to provide an envelope, which was a feature of the digits, and to also clearly distinguish the cue from the subsequent white noise target that was not amplitude modulated.

Cues and targets were then processed to elicit realistic spatial perceptions of locations outside of the participant's body, as when perceiving natural sounds. These "virtual" sound locations were created by adding appropriate differences in interaural time, level, and head related transfer functions for each intended location (SLAB software, National Aeronautics and Space Administration). Cues were all presented at the midline (0°). Targets were presented at one of nine locations in virtual space (0° midline, ±2°, ±4°, ±6°, ±12° to the left and right of midline). By convention, negative degree values are locations to the left of midline and positive values are to the right of midline. The virtual locations were chosen based on a previous study (Golob, Lewald, et al., 2017). There is substantial variability within and between individuals in spatial hearing (Blauert, 1997), but impressions of the participants as well as the behavioral data indicate that the sounds were perceived at the intended locations.

Procedure

Each trial had a cue that was followed by a target that required a left/right judgment relative to midline. On a given trial the cue was either a digit from 1–9 or the amplitude modulated white noise stimulus (p = .10 for each stimulus). After a 1.0-s stimulus onset asynchrony (SOA) the white noise target was presented. Participants then judged whether the target was to the left or right side of their subjective midline and pressed one of two buttons with either their corresponding left or right hand to indicate their choice. Midline was explained as the location straight ahead relative to the middle of their head, and all participants understood the idea. Participants were instructed to respond at a pace that ensured they provide accurate judgements of left or right stimulus location. The SOA between onset of the target and the next cue was 2.0 s. Each participant received 6 blocks of 90 trials/block (540 total trials). Within each block of 90 trials, targets were presented once at each of the nine stimulus locations following each of the ten cues (nine digits, one white noise).

Data Analysis and Statistics

The dependent variable was the PSE derived from fitting a Weibull function to the white noise target by using the proportion of right judgments at each target location (0°, ±2°, ±4°, ±6°, ±12°). The Palamedes toolbox for Matlab was used for curve fitting (Prins & Kingdom, 2018). Ten separate PSEs were quantified, one for each cue (digits 1–9, white noise control). The four parameters of the Weibull function were: the PSE, the slope of the psychometric function, and the minimum (gamma) and maximum (lambda) parameters at the asymptote of 0 and 100% right responses. Gamma and lambda were fixed at .05; results with these parameters at .01 yielded the same patterns of results reported below. Psychometric slope data were not presented here because the main question concerned the participant's judgment of sound location, rather than details on psychometric function shape. Data were measured and entered into a spreadsheet during data collection. Based on our previous findings when judging number stimuli, we used analysis of variance (ANOVA) tests with a factor of location (9) and a linear contrast of PSE as a function of number magnitude (Golob, Lewald, et al., 2017). For clarity, the original degrees of freedom values are given in the results, however Greenhouse-Geisser corrections were performed when appropriate. p values were limited to two decimal places.

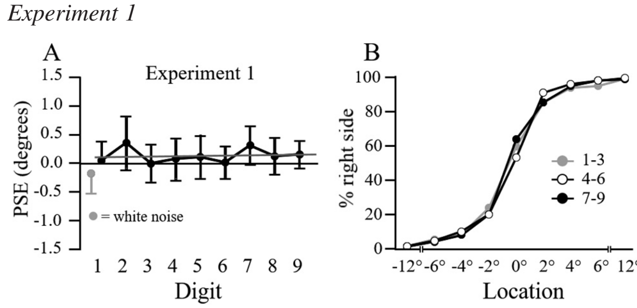
Results

A plot of PSE × Number Magnitude is shown in Figure 1A, with grand average psychometric functions shown in Figure 1B. A one-way ANOVA with the factor of number (9) had a nonsignificant effect (F[8, 120] = .3; p = .96, η_p^2 = .02). The correlation between PSE and number magnitude was also not significant (linear contrast: r = .11, p = .87, η_p^2 = .02). As expected, the psychometric functions were steep near the midline, showing that the locations were clearly distinguished.

Discussion

The results from Experiment 1 provided no support for the idea that spatial codes associated with recently spoken numbers can bias location judgments of white noise targets. Data collection stopped at 16 participants because it was very obvious that the expected association between number value and PSE was not evident in the data (ANOVA p = .96, η_p^2 = .02; r = .11). For an effect size of r = .11, approximately 646 participants would be needed to attain significance under standard power assumptions (p < .05,

Figure 1
Experiment 1



Note. (A) Plot of point of subjective equality (PSE) vs. digit. The grey data point indicates PSE for white noise stimuli. (B) Psychometric function plotting sound location against % right side judgments for digits grouped by small (1–3), medium (4–6), and large (7–9) values within the range of 1 to 9. Each participant had a psychometric function averaged from the three digit values in each range, and the plot shown was from averaging across participants. There was no significant association between digit value and PSE. Error bars show standard error of the mean.

$1 - \beta = .80$). The absence of a significant magnitude effect here stands in contrast to our previous study that found such an effect when participants pointed to mostly lateral sound locations (Golob et al., 2016). There are notable methodological differences between the studies, such as presenting sounds at midline versus lateral sound locations and measuring spatial perception using a left/right judgment versus a pointing response. The importance of using a midline criterion versus other locations is shown by a study that found different effects of number value when the left/right reference frame was centered around lateral (±18°) versus midline locations (Golob, Lewald, et al., 2017). Sound localization is also known to vary depending on variables such as eye position, posture, and method of indicating the perceived location (Lewald et al., 2000; Lewald & Ehrenstein, 1996).

Experiment 2

One possibility for why hearing a number shortly before making a spatial judgment had no significant effect is that participants did not adequately encode the number into STM. This may be particularly important when number information has to be retained for a short period of time, and less important when making an immediate judgment of a number itself, as was previously done (Golob, Lewald, et al., 2017). To test this idea we used the same paradigm as in Experiment 1, except now participants had to remember the digit. After every cue–target pair a digit was presented as a recognition probe (Sternberg, 1966). Participants judged whether the probe digit was a match or mismatch to the digit in memory and pressed one of two buttons to indicate their choice.

Method

Participants

A new group of 25 participants was recruited (age = 20.4 ± .6; M/F = 12/13 women, 22/25 right handed). The participant number was based on the power analysis in Experiment 1. They received the same screening procedures as in Experiment 1, and none were excluded.

Materials and Stimuli

The apparatus, materials, and stimuli were the same as those used in Experiment 1. The white noise sound used in the previous experiment was not included because results in Experiment 1 showed that judgments did not differ from the objective midline.

Procedure

Experiment 2 had the same basic design and analysis as Experiment 1. The only differences were (a) after listening to the digit cue and white noise target, a probe digit was then presented (1,500 ms SOA), and (b) seven locations (0°, ±2°, ±4°, ±12°) were used instead of nine. Fewer locations made time to add the probe while maintaining the same number of trials as in Experiment 1 (±6° locations were excluded). The digit cue and probe stimuli were the same stimuli. The interval between the probe and the cue of the next trial was 2,000 ms. Probe digits were randomly selected from 1–9 and were equally likely to be a match/mismatch to the cue digit. Participants were instructed to respond at a pace that ensures they provide accurate judgements of left or right stimulus location and probe match or mismatch. If participants did not respond within 1.9 seconds to the probe it was counted as a "no response." If participants responded incorrectly to the probe or did not respond before the next cue the trial was also discarded to ensure they had accurately retained the digit in memory. Participants received a total of 630 trials evenly divided between 10 blocks. There were seven trials per cue, per location, per block that were randomized and counterbalanced.

Data Analysis and Statistics

The data analyses and statistics were the same as in Experiment 1, except for an additional analysis of STM accuracy. A planned linear contrast of PSE against digit magnitude was based on (Golob, Lewald, et al., 2017).

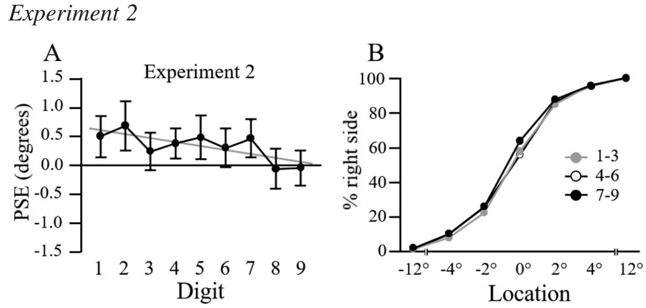
Results

Participants were very accurate in determining whether the probe matched the cue number (M = 96.6 ± .7%), and accuracy did not significantly vary across the nine digits. In Figure 2, plots of PSE versus number magnitude (Figure 2A) and psychometric functions for digits averaged between 1–3, 4–6, and 7–9 (Figure 2B) are presented. A one-way ANOVA with a factor of number magnitude (9) had a significant effect ($F[8, 192] = 2.4$; $p < .03$, $\eta_p^2 = .09$), as did the a priori linear contrast ($r = -.74$; $F[1, 24] = 11.6$; $p < .01$, $\eta_p^2 = .33$).

Discussion

Experiment 2 showed that having to retain the numeric value of the cue in short-term memory was sufficient to reveal a bias of number magnitude in memory on concurrent spatial judgment of sound location. This memory-based numeric bias matched what was seen when making spatial judgments of number stimuli, with a rightward shift in PSE for small numbers that moved leftward as number magnitude increased (Golob, Lewald, et al., 2017). This shows some generality of the number influence on auditory spatial judgments, as the effect was entirely from memory. Similar results have been observed using visual search, where retaining the shape and color of a pretrial prime in STM influences search perfor-

Figure 2
Experiment 2



Note. (A) Plot of point of subjective equality (PSE) vs. digit. (B) Psychometric function showing sound location vs. % right side judgments for digits grouped by small (1–3), medium (4–6), and large (7–9) values. When participants retained the digit in short-term memory there was a significant linear association between digit value and PSE (p = .002). Error bars show standard error of the mean.

mance, while only attending to the prime is insufficient (Soto & Humphreys, 2007).

Evidence suggests that coding in short-term memory is based more strongly on phonological and semantic coding, rather than basic sensory features (Baddeley & Hitch, 1974). For example, work on echoic memory shows that within a couple of seconds vivid sensory information is recoded for retention in STM (Cowan, 1984), although the precise relations between sensory and STM are complex (Nees, 2016). Our prior work on spatial perception of digits considered whether the physical features of digit sounds may covary with digit magnitude (for details see Golob, Lewald, et al., 2017). This possibility was viewed as unlikely for several reasons, including the findings that numeric spatial biases for digits spoken in English and German were similar, experimental factors affected spatial biases for the same digit stimuli, and because of the arbitrary nature of the assigning speech sounds to name digits (Golob, Lewald, et al., 2017).

In addition to our task's explicit memory requirements, there may also be implicit memory for the range of numbers across trials. This is important because number biases can index relative magnitudes. For example, the number "10" is large in the range of 1–10 but small in the range of 10–100; and left-right numeric bias can scale to the range of numbers that are being tested (Dehaene et al., 1993). The exclusive use of single digits is another consideration, as magnitude coding may be particularly strong for commonly used digits. Lastly, although number cognition studies often consider numbers to reflect a magnitude code, magnitude also covaries with the order of numbers. The distinction between magnitude and order is becoming important for determining whether spatial codes are retained in long term memory, as is conventional (Nieder & Dehaene, 2009), or are instead generated through a STM mechanism (Abrahamse et al., 2016). The present set of studies focused on the nature of presumed spatial codes in STM that may bias perception. The question of how those spatial codes got to be in short term memory, either passed on from long-term memory or created by STM mechanisms, will not be explored here.

Experiment 3

Spatial perception in Experiments 1 and 2 was directly assessed by having participants make left/right judgments of a single stimulus relative to their midline. The findings showed the importance of having a memory demand for the emergence of a numeric spatial bias. In Experiments 3–5 we broaden the examination of numeric spatial bias from STM on auditory spatial perception by using a dichotic listening task. In dichotic listening two stimuli are presented at the same time, one to the left ear and one to the right ear, and the stimuli compete for perceptual awareness (Broadbent, 1958; Kimura, 1967). There are many task variations (Cutting, 1976); but here we will use consonant vowels, such as /da/ and /ka/. The consonant-vowels induce an ambiguous percept (or "perceptual fusion") by having the same duration, intensity, and spectral range (Bregman, 1990). The consonants distinguish left from right stimuli, which are then followed by the same vowel. One of the two consonant-vowels usually predominates on a given trial, and participants are asked to report the consonant-vowel that they heard best.

The use of dichotic listening judgments puts additional distance between the task demands and spatial codes in memory because the task itself does not require the participant to make spatial judgments. Spatial information is inferred by noting which ear received the consonant-vowel that the participant heard best on each trial. Thus, spatial coding is indirect; the fused consonant-vowels are perceived at the interaural midline, and the instruction to judge the consonant-vowel that was heard best does not mention space at all.

Lastly, dichotic listening has a pronounced spatial bias known as the "right ear advantage." Under the divided attention conditions of our paradigm participants are about ~50% more likely to report the consonant vowel that was presented to the right ear (Hugdahl, 2003; Yurgil & Golob, 2010). Here we will test whether numbers in STM can have a similar influence on the right ear advantage. In addition to the right ear advantage, on about 10–20% of trials participants report hearing a consonant-vowel that was not a part of the dichotic stimulus, which we term "intrusions." Intrusions will also be examined as a function of the numbers in STM, as this gives insight into numeric information may influence how stimulus information is assembled to generate a perceptual report.

Method

Participants

A new group of young adults were recruited from University classes and received extra credit for participation (n = 14, age 20.0 ±1.3 years., M/F = 9/5, 11/14 right-handed). Participants were given the same screening procedures for neurological disorders and hearing ability as in the previous experiments, and all had English as their first language. Six additional participants were tested, but the data were not available due to experimental error and equipment failure. Based on the substantial effect of number magnitude in Experiment 2, a sample size of 20 participants was chosen for the dichotic listening method used in Experiments 3–5. As shown below, the main findings were replicated across experiments. After the main experiment participants then performed a pilot experiment that is not reported here.

Experimental Design

Experiment 3 used the basic design of Experiment 2 by first presenting a single digit between 1 and 9 to be retained in STM, then a series of dichotic stimuli requiring perceptual judgments, and lastly participants were asked to recall the number in memory. The two dependent variables for dichotic listening were the laterality index (described below) to compare reporting of the left versus right ear consonant-vowel, and the percent of intrusions.

Materials and Stimuli

The same acoustic numbers were used for memorization as in the experiments above. Acoustic consonant-vowels were sampled at 44.1 kHz from the same adult male and were chosen to differ in their initial stop consonant (/da/,/ga/,/ka/,/ta/). Prior work has shown that a stop (also termed "plosive") consonant followed by a vowel yields a larger right ear advantage relative to other speech sounds (Shankweiler & Studdert-Kennedy, 1967). All were edited to last 250 ms and were presented at about ~60 dB nHL, with equal intensity at each ear. The spatial percept of the fused consonant-vowels was centered at midline along the interaural axis. Consonant-vowels were presented in all 12 possible combinations of different consonant-vowel pairs and ears. There were six combinations of the different consonant vowels, and a given pair of consonant vowels (CV_1 and CV_2) could be presented to the ears in two combinations (CV_1-left and CV_2-right, or CV_1-right and CV_2-left).

Procedure

In each trial participants were first presented with an auditory STM load of one digit (1–9), as above. After an SOA of 4 s they heard four pairs of dichotic consonant-vowel sounds (4 s SOA between consonant-vowels). After each dichotic stimulus participants pressed one of four buttons on a keypad to indicate which of the four consonant-vowels they perceived best. Going from left to right, the four keys were mapped to the consonant vowels in alphabetical order for all participants (/da/,/ga/,/ka/,/ta/). A card showing the mapping between consonant-vowel and key was placed in front of the participants if needed, although participants rapidly acquired the mapping between the consonant vowels and the corresponding keys. Lastly, participants saw a visual prompt to verbally recall the memorized number (4 s SOA from last consonant-vowel). Each block had 15 trials, with four pairs of consonant vowels per trial, giving a total of 60 consonant vowel judgments. Within participants each digit was memorized a comparable number of times (six or seven), which was further balanced-out across participants. Trials with incorrect recall were excluded from analysis.

Data Analysis and Statistics

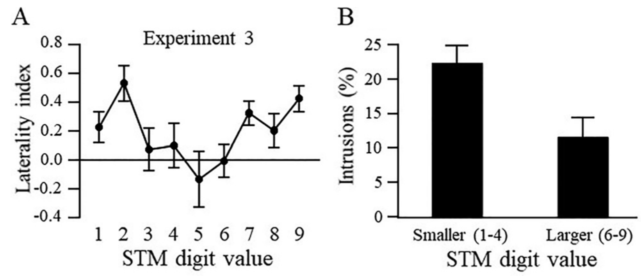
Laterality indexes for each digit in memory were calculated using the formula (# trials right ear − # trial left ear)/(# trials right ear + left ear). Data were analyzed using one-way ANOVA tests with the factor of number magnitude in memory (9). For comparison with experiments below that had more than one digit in memory digits were grouped into a smaller (1–4) and larger (6–9) range for analysis. There were relatively few intrusions. Consequently, for analysis of intrusions they were also grouped into small (1–4) and large (6–9) number magnitudes.

Results

Participants were 98 ± 1% accurate in judging whether or not the STM probe matched the number at the beginning of the trial. The laterality index and intrusion results with one number in memory are shown in Figure 3 When the mean laterality index of small (1–4) and large (6–9) numbers were compared there was not a significant difference (paired t test, $t[13] = .1$, $p = .96$). Analysis of laterality index using a one-way ANOVA for digit magnitude (9) had a main effect of magnitude ($F[8, 104] = 3.7$; $p < .02$, $\eta_p^2 = .22$). As shown in Figure 3A, the magnitude effect was attributable to smaller laterality index values for the digits in the middle range of values and typical right ear advantages for the other digits.

For the analysis of intrusions, there was a significant difference between smaller and larger digits in STM ($t[13] = 4.0$; $p < .01$, $\eta_p^2 = .56$), with nearly twice as many intrusions when the digit was in the small range (digits 1–4, 22.1 ± 2.4%) relative to the large range (digits 6–9, 11.5 ± 2.9%). Across participants, 13/14 had more intrusions with the small digits in memory. Memory

Figure 3
Experiment 3



Note. (A) Laterality index in dichotic listening as a function of the digit value in short-term memory. The laterality index had the smallest values for the middle of the digit range. (B) Intrusions in smaller (1–4) and larger (6–9) ranges. Significantly more intrusions were observed with smaller digits in memory ($p = .001$). STM = short-term memory. Error bars represent standard error.

performance was nearly perfect, and inclusion of participants without memory recognition data had the same results as above.[2]

Discussion

Unlike Experiment 2, having one digit in memory did not lead to a left-right bias in the laterality index that would covary with number magnitude in memory. Instead, digits in the middle of the range had the smallest laterality index values. This may reflect the significance of the middle of the range within the canonical set of digits. Although recall data were available for only 14 participants tested, note that the results from Experiment 3 were fully replicated in Experiment 5 below.

There was a strong influence of digit magnitude on intrusions, which were much more likely when numbers in the smaller range were held in memory. As in other modalities, recognition in auditory scenes is thought to be a constructive process that attempts to map sensory data onto discrete perceptual objects, in this case reflecting sources of sound in the environment (Bregman, 1990). We speculate that preferential processing of left ear stimuli when categorizing the consonant-vowels might increase intrusions. Dichotic listening is often used as a metric to study hemispheric differences (Hugdahl, 2003), a premise largely based on the right ear advantage. The right ear advantage is classically thought to reflect heightened access to left hemisphere speech and language areas due owing a contralateral bias of right ear input (Kimura, 1961b, 1967; Milner et al., 1968; Springer & Gazzaniga, 1975). More recent data suggest that speech is processed in both auditory cortices, but rapid segments reflecting consonants may be

[2] Although six participants did not have memory accuracy measures, they were from the same pool as the other 14 participants who performed at ceiling and were probably very accurate. If we include all 20 participants, the results and conclusions do not differ from the main analysis using the 14 participants with recall data. Analysis of laterality index using all 20 participants had a main effect of magnitude ($F_{(8,152)} = 3.4$; $p = .009$, $\eta_p^2 = .15$). For the analysis of intrusions, there was a significant difference between smaller and larger digits in short-term memory ($t_{(19)} = 3.7$; $p = .001$, $\eta_p^2 = .42$), with more intrusions when the digit was in the smaller range (digits 1–4, 20.9 ± 2.1%) relative to the large range (digits 6–9, 12.7 ± 2.4%).

disproportionately handled by the left auditory cortex, while vowels and longer-lasting suprasegmental elements are more related to right auditory cortex activity (Hickok & Poeppel, 2000). In the current task rapid spectral features distinguish the four consonants, which suggests that right ear-left hemisphere processing of segmental information is particularly important for accurate consonant-vowel judgments. If smaller digits in memory were to enhance the left ear-right hemisphere processing of vowels, then intrusions could increase due to random consonant-vowel judgments driven by uninformative vowel information.

However, in Experiment 3 the enhancement of left ear processing was in the middle of the number range rather than the smaller end. Stronger evidence would be a robust left ear laterality bias with small numbers in STM that is also accompanied by increases in intrusions. The next experiment will address this possibility by increasing the STM load during dichotic listening up to two and four digits.

Experiment 4

Prior work has shown distinct effects of having one item in STM versus at least two items, using both behavioral (McElree & Dosher, 1989) and neural (Golob & Starr, 2004a) measures. A related line of work has proposed that number biases in STM may be related to serial position coding, with a leftward bias for initial numbers in a series that becomes a rightward bias for later numbers (Abrahamse et al., 2016). Experiments 4 and 5 will test whether the magnitude of numeric STM perceptual biases is affected by having more than one item in memory. In Experiment 4 participants did the same dichotic listening task as in Experiment 3, but now they retained either two or four digits in memory. The digits in STM were classified into trials that had sets of only smaller (1–4), only larger (6–9) or mixed (half smaller, half larger) digit values.

Method

Participants

A new set of young adults were recruited (n = 20, age 20.4 ± 2.9 years., M/F = 9/11, 17/20 right-handed). In addition, a separate group was recruited for a comparison condition that used the same paradigm described below but did not have a STM load (n = 20, age 21.6 ±3.5, M/F = 7/13). Participants were given the same screening procedures for neurological disorders and hearing ability as in the previous experiments.

Materials and Stimuli

The materials and stimuli used in Experiment 3 were also used here.

Procedure

Participants did the same task as in Experiment 3 except now they were given two or four digits to remember during each set of four dichotic listening trials. For simplicity, load was consistent within a block of trials. Each block had 15 trials with four dichotic stimuli/trial, and the order two or four item memory loads was counterbalanced across participants. A total of 120 dichotic stimuli were given, with sixty dichotic stimuli for each STM load (2 or 4 digits). The SOA between digits was 4 s, and as before was then followed by four dichotic trials and then a cue to recall the memorized digits. There were three types of memory sets, defined by the magnitude of numbers that were in the set. On some trials participants were only given smaller numbers, from 1–4, or larger numbers from 6–9. On mixed trials numbers from the smaller and larger range were both included. For mixed trials with two digits, one was smaller (1–4) and the other larger (6–9). Mixed trials with four digit loads had two smaller and two larger digits. The three trial types were given an equal number of times (5 of each trial type in each level of memory load). The digit “5” was not included as a memory item, to have a range of four digits in both the smaller and larger sets. Digits were not presented twice in a given memory set. As in Experiment 3, the frequency of including each digit in the memory sets were approximately balanced within and across participants. If recall was incorrect results from the four dichotic judgments on that trial were not included in the analysis.

To define a baseline for laterality index and intrusions when participants were not retaining items in STM the same experiment was run without numeric stimuli. This was done by replacing the acoustic numbers before the dichotic stimuli with white noise (100–10,000 Hz, 400 ms duration, ∼60 dB nHL). The recall cue was replaced by “XXXXX.”

Data Analysis and Statistics

The dependent variables were laterality index and percentage of intrusions as defined above. Analysis of variance tests had factors of STM number magnitude (smaller 1–4, and larger 6–9), and memory load (two or four digits). Post hoc testing used paired comparisons with Bonferroni correction for multiple comparisons.

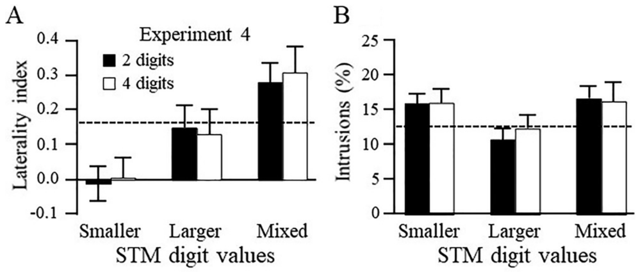
Results

We will first present the results from the control Condition without a memory load, followed by loads of two and four digits. The laterality index and intrusion results are shown in in Figure 4. The laterality index in the control Condition was .16 ± .05 and is represented by the dotted line in Figure 4A A one-sample t test against 0 showed the expected significant right ear bias (t[19] = 3.0, $p < .01$, Cohen’s d=.65). The laterality indices for two versus four tones at the beginning of each block were about the same (two tones = .16, four tones = .15). Intrusions occurred on 12.5 ± 1.2% of trials (dotted line in Figure 4B).

For the main experiment dichotic listening performance was tested when two or four digits were held in STM. Participants were 95 ±1.1% accurate in recalling the numbers from the beginning of the trial, with no significant difference between loads (two digits = 96 ±1.1%, four digits = 94 ±1.9%, p = .3). A 2 (magnitude: smaller, larger) × 2 (load: two, four items) ANOVA test showed a significant main effect of magnitude (F[1, 19] = 7.1; $p <$ .02, η_p^2 = .27), indicating a smaller laterality index for smaller versus larger digits in memory (.00 ± .04 vs. .14 ± .06, respectively). There was no significant effect of load, and the Magnitude × Load interaction was also not significant.

In mixed trials the laterality index did not differ between loads (p = .67). Paired comparisons showed that laterality index for mixed trials was significantly larger than the smaller (t[19] = 5.02, $p < .01$, η_p^2 = .57) and larger (t[19] = 3.12, $p < .01$, η_p^2 = .34) magnitude conditions. One-sample t tests relative to 0 had significant

Figure 4
Experiment 4



Note. (A) Laterality index as a function number values in short-term memory (STM) and load (two or four different digits). Results showed that the right ear advantage was abolished with smaller numbers in memory, comparable to no load with larger numbers, and largest with a mix of smaller and larger numbers in memory. (B) Intrusions as a function of number value and memory. Intrusions were less likely with larger numbers in memory vs. smaller and mixed numbers. The horizontal dotted lines show the means of the control group without a memory load. STM = short-term memory. Error bars represent standard error.

differences for high ($p < .03$) and mixed ($p < .001$) numbers in memory but not for small numbers ($p = .93$). This shows that the right-ear advantage was largest for mixed loads versus larger loads and was not evident when small numbers were in memory.

The percent of intrusions was tested with a Magnitude (2: smaller, larger) × Load (2) ANOVA test, which had a significant effect of magnitude ($F[1, 19] = 6.3$; $p < .03$, $\eta_p^2 = .25$). The magnitude effect was attributable to having more intrusions when smaller digits were held in memory (smaller: 15.9 ±1.5 vs. larger: 11.5 ± 1.3%). Intrusions on mixed trials did not differ between loads ($p = .90$). Paired comparisons showed no difference between mix and the smaller digit trials ($p = .72$), and a small difference when large digits were in memory ($t[19] = 2.3$, $p < .04$).

Discussion

The main results of Experiment 4 were: (a) having a set of small digits in memory eliminated the right ear advantage, (b) intrusions were more frequent with smaller versus larger digits in memory, and (c) the right ear advantage was greatest when a mixed set of digits was held in memory versus homogenous memory sets of only smaller or larger digits. The major difference between Experiment 3 (one digit load) was that a set of two or four smaller digits facilitated processing of the consonant-vowel to the left ear, which abolished the right ear advantage. As in Experiment 3, with loads of two or four digits there were significantly more intrusions when retaining smaller versus larger digits.

There are many combinations of multiple digits in STM, that were approximately counterbalanced. This experiment did not have enough trials to make precise comparisons of combinations such as whether having "1" and "2" in memory had a smaller laterality index versus retaining "3" and "4" in memory. Future work could test whether there is a systematic increase with pair magnitudes or the average magnitude in STM, which would be similar to the analysis in Experiment 2 using left/right spatial judgments.

There were no differences between laterality index or intrusion measures among the two and four item loads. As is common in simple recognition tasks, accuracy was near ceiling for both loads, although it was numerically lower in the four item load. Thus, behavioral data suggest that the effective memory load was comparable in the two and four item loads. Another consideration is that in the four item Condition trials with smaller or larger numbers used all of the available digits within each range (1–4 or 6–9). This regularity could permit a strategy of retaining the range (smaller or larger), which could reduce the effective memory load by excluding half of the digits. With enough practice, participants can pick-up similar contingencies in short-term recognition tasks (Schneider & Shiffrin, 1977).

The finding that a mix of smaller and larger digits in memory had a significantly larger laterality index relative to control and larger memory set conditions was not predicted. We defer more detailed discussion until later, to first replicate this finding. We note that the very large right ear advantage induced by mixed numbers in memory is intriguing because it exceeds typical participant performance when intentionally attending to the right ear (Hugdahl et al., 2009). Thus, there seems to be an automatic influence that, unlike most other instances in the perception and attention literature, leads to superior performance relative to when the participant consciously tries to get the same results. This is extremely unusual.

The objective of the final experiment was to try to replicate Experiments 3 and 4 using a within subject analysis. Each participant was tested with STM loads of 1–4 items.

Experiment 5

Experiments 3 and 4 showed that having numeric information in STM while performing a dichotic listening task impacted perception in two ways. The first was an influence on ear biases, and the second was on the percent of intrusions. However, the number magnitudes that impacted dichotic performance were not the same for Experiments 3 and 4. In Experiment 4 the findings were comparable with either two or four digits in memory, and the numeric bias that counteracted the right ear advantage occurred with small numbers in memory (1–4). When one digit was in memory there was no difference in laterality index for numbers in the smaller versus larger digits. Instead, the right ear advantage was reduced for memory digits in the middle of the number range. In both experiments there were more intrusions with smaller versus larger numbers in STM. Experiment 4 also revealed that the laterality index for mixed trials was larger than when digits were restricted to only the smaller or larger number sets. In Experiment 5 we wanted to evaluate the consistency of these results by testing memory loads of between one and four digits using a within participants design.

Method

Participants

A new group of twenty participants was recruited for Experiment 5 ($n = 20$; age 18.8 ±1.0 yrs., M/F = 5/15, 20 right-handed). Participants were screened for neurological and hearing impairments as in the previous experiments.

Experimental Design

Memory load was tested in separate blocks where trials had one, two, three, or four digits in STM. The order of blocks was approximately counterbalanced across participants.

Materials and Stimuli

The materials and stimuli were the same as in Experiment 4.

Procedure

The task was the same as in Experiments 3 and 4. In each trial between one and four unique digits were presented, followed by perceptual judgments of four dichotic stimuli, and then participants attempted to recall the digit(s). A total of 60 dichotic listening stimuli were given per memory load (240 total), in 15 trials (four dichotic stimuli/trial). Each block had the same memory load in all trials, and the order of memory loads was approximately counterbalanced across participants. If recall was incorrect for a trial the four dichotic listening judgments from that trial were not included in the analysis.

Data Analysis and Statistics

The dependent variables were laterality index and percentage of intrusions. Analysis of variance tests had factors of STM number magnitude (smaller 1–4, and larger 6–9), and memory load (two, three, or four digits). When one item was in memory the laterality index was also calculated for each digit. Post hoc testing used paired comparisons with Bonferroni correction for multiple comparisons.

Results

The one item memory load will be presented first because it had a qualitatively different pattern for the laterality index measure relative to loads of 2–4. The combined analysis of loads 2, 3, and 4 will then be presented.

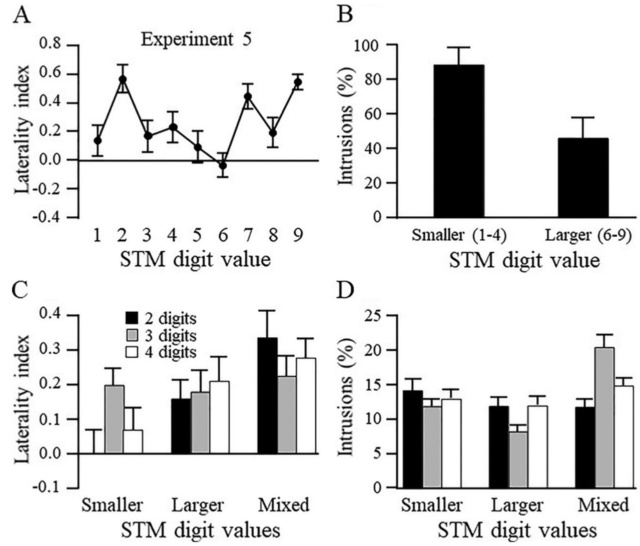
Memory Load of One Item

In the one item load Condition participants were 99 ± .7% accurate in recalling the digit from memory. A paired *t* test comparing the laterality index for digits in the smaller (1–4) and larger (6–9) ranges was not significant (p = .99). A one-way ANOVA for digit magnitude (9) had a main effect of magnitude (F[8, 152] = 7.91; $p < .01$, $\eta_p^2 = .29$). As shown in Figure 5A, the magnitude effect seen in Experiment 3 was replicated, with digits 5 and 6 having more negative laterality index values than the other digits. Results from Experiment 3 suggested a quadratic curve for the Digit × Laterality index function and quadratic modeling was significant ($p < .01$). Examination of intrusion percentage showed that intrusions were more common for smaller versus larger digits in memory (t[19] = 5.2; $p < .01$, $\eta_p^2 = .59$; Figure 5B).

Memory Loads of Two, Three, and Four Items

Across the two, three, and four item loads, participants were 97 ± 1.2% accurate, with no significant difference among loads (two digits = 98 ±1.2%, three digits = 97 ±1.0%, four digits = 95 ± 1.3 %, p = .40). For loads with more than one digit in memory the analyses of laterality index and intrusions used 2 (magnitude: small, large) × 3 (load: two, three, four memory items) ANOVA tests (Figure 5C). The laterality index had significant main effects of magnitude (F[1, 19] = 9.8; $p < .01$, $\eta_p^2 = .34$) and load (F[2, 38] = 5.07; $p < .02$, $\eta_p^2 = .21$; Figure 5C). The Magnitude × Load interaction was nonsignificant ($p < .06$, $\eta_p^2 = .15$).

Figure 5
Experiment 5



Note. One-digit memory load measures of laterality index (A) and intrusions (B). Two, three, and four digit memory loads and laterality index (C) and intrusion (D) measures. STM = short-term memory. Error bars represent standard error.

A separate analysis of the laterality index for mixed trials using a factor of load was not significant (p = .34; Figure 5C). Paired comparisons collapsed across loads of two to four items showed that the laterality index was significantly larger for mixed versus smaller digits (t[19] = 5.4, $p < .01$, $\eta_p^2 = .61$), as well as larger digits (t[19] = 2.2, $p < .04$, $\eta_p^2 = .21$). One-sample *t* tests relative to 0 indicated a significant right ear advantage with mixed (t[19] = 5.4, $p < .001$) and larger (t[19] = 3.2, $p < .01$) and numbers in memory, but not for smaller numbers (p = .13).

For the analysis of intrusions under memory loads of two to four items there was a main effect of load (F[2, 38] = 3.7; $p < .04$, $\eta_p^2 = .17$). The magnitude main effect was not significant (p = .073, $\eta_p^2 = .16$). The load effect was due to fewer intrusions in the three item load (10.0 ± .8%) versus two and four items (12.9 ± 1.0 and 12.4 ±1.2%, respectively; Figure 5D).

Intrusions on mixed trials were examined with a one-way ANOVA using the load factor, and there was a significant load effect (F[2, 38] = 13.5; $p < .01$, $\eta_p^2 = .42$). Paired comparisons showed that with three items in memory there were more intrusions relative to loads of two (t[19] = 4.9; $p < .01$) and four (t[19] = 3.0; $p < .01$).

Discussion

Most of the findings in Experiment 5 replicated what was found in Experiments 3 and 4. With one digit in memory the laterality index was smallest around the digits 5 and 6, relative to smaller and larger numbers. With two to four items in STM the laterality index was lower when retaining smaller versus larger numbers, with a nonsignificant right ear advantage when smaller digits were in memory. The magnitude effect did not significantly vary with load size. Having a mixed set of smaller and larger digits in memory again had the largest laterality index. Intrusions were more frequent with smaller digits in memory in the one item load condition, and this was at the level of a trend in the two to four item load conditions. Overall, these results show that the content in STM can influence two aspects of perceptual judgments in the dichotic listening task: the presumed competition between left and right ear stimuli, and the ability to make a veridical judgment about the consonant-vowels that comprise the dichotic stimuli.

The three item load had two atypical patterns relative to loads of two and four. Although the interaction was not significant, the laterality index did not show a reduction with smaller numbers in STM. The second difference was that when a mixed set of digits was memorized intrusions were significantly more likely when remembering three items versus two or four items. The reason for such a difference is not clear, although it may relate to having an imbalance between smaller and larger digits (i.e., two larger/smaller digits and one of the other) or even versus odd numbers. The digit "5" was also inadvertently included in the memory sets with three items but was excluded for sets of two and four items (as in Experiment 4). Potential differences between a load of three versus two or four items is not a major point in this study and would need to first be replicated before engaging in too much speculation.

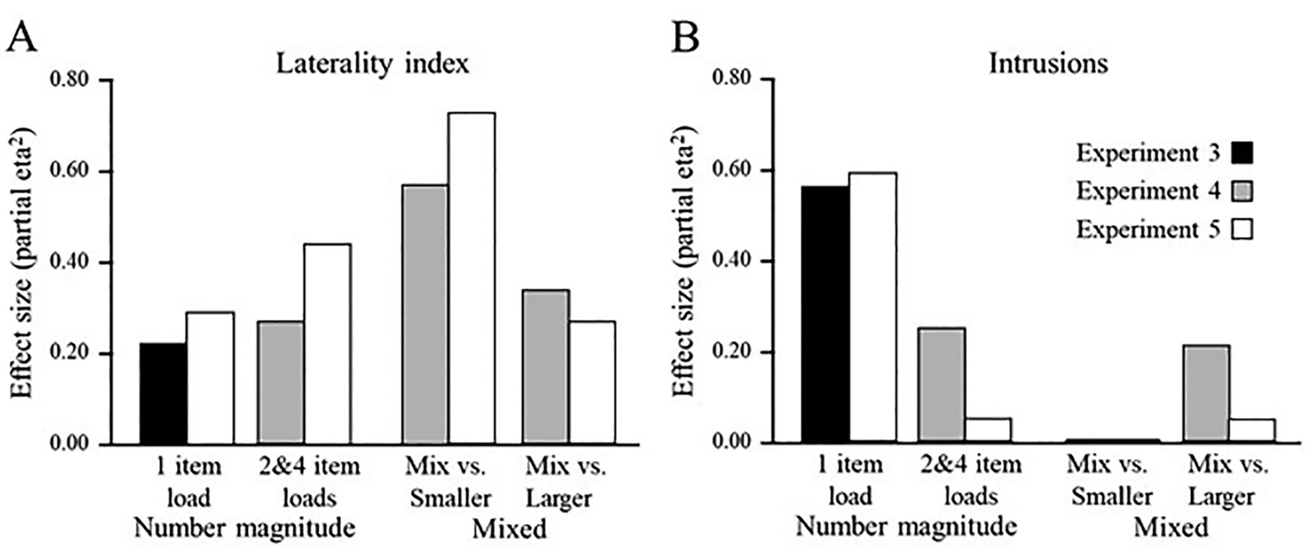
General Discussion

This study tested the hypothesis that the magnitude of numbers in STM would impart a spatial bias on perceptual judgments of concurrent acoustic stimuli, with smaller numbers biased to the left and larger numbers biased to the right. In the first two experiments participants made direct perceptual judgments of sound location relative to the midline (left vs. right side). In Experiments 3–5 location was indirectly tested by having participants report the consonant vowel of a dichotic stimulus that was perceived best, and the ear that received the reported consonant vowel was noted. A summary of the effect sizes (η_p^2) for the three dichotic listening experiments is shown in Figure 6, and shows mostly consistent effects across experiments. The effect sizes for Experiment 1, which did not have memory instructions and memory probes, and Experiment 2, which did include memory instructions and probes, were η_p^2 = .02 (Experiment 1) and η_p^2 = .33 (Experiment 2).

The main findings across experiments were that smaller digits in memory biased perceptual judgments to the left and larger digits biased perception to the right (Experiments 2, 4, 5). For left-right judgments the numeric spatial bias was absent when participants did not have to memorize the digits (Experiment 1). For dichotic listening at least two digits needed to be in STM before a left-right bias was evident (Experiment 3). Unexpectedly, a mixture of smaller and larger digits in memory had the largest right ear bias of any condition (Experiments 4, 5). Lastly, having smaller numbers in memory made intrusions more likely in the dichotic listening task (Experiments 3, 4, 5). Overall, the findings provide convergent evidence that numeric contents in STM exert a top-down bias over perception of auditory spatial location.

The current findings agree with other studies showing that having information in STM affects behaviors such as RT (Olivers et al., 2011; Soto et al., 2008). These results expand our knowledge by (a) showing memory effects on a basic element of conscious awareness (spatial location) rather than performance (speed or accuracy), and (b) the contents of STM that generate the bias are indirect, by virtue of an association between number magnitude (or ordering of numbers) and left-right egocentric space. Note that these STM effects during a dual task situation are distinct

Figure 6
Effect Sizes in Dichotic Listening Experiments (3-5)



Note. Laterality index (A) and intrusion (B) measures measure as a function of number magnitude (left sides) and comparisons of mixed vs. smaller or larger numbers (right sides) in memory. Effect sizes are partial eta^2.

from context effects when listening to sentences in noise (Pichora-Fuller et al., 2016) or priming effects that carryover to perceptual judgments (Riecke et al., 2011). The indirect nature of relations between number magnitude and space, particularly in dichotic listening tasks where participants are not asked to directly make spatial judgements, also likely reduces the risk of subject demand. Lastly, (c) the bulk of the literature examines how STM can influence visual search. Convergent evidence from the auditory modality using perceptual tasks can help to test the generality of these STM biases.

Tasks and Spatial Judgments

The two different tasks allowed us to evaluate whether any spatial biases by numbers in memory generalize to different measures of what the participant perceives. The first two experiments used a left/right judgment task as a direct measure of spatial perception; and only when participants were required to remember the digits (Experiment 2) was there a linear relation between digit magnitude and the location of subjective midline (the PSE). Thus, the contents of memory were able to subtly, but systematically distort how participants perceived external space. A concern of directly making spatial judgments is that participants may have adopted left-right number line heuristic as a response strategy (i.e., making more left responses to "1" and more right responses to "9", with appropriate scaling for the in-between digits). This is unlikely, as the small, linear range of the PSE between digits 1–9 ($\sim$1°) would be very difficult to fake. In addition, participants did not adopt such a strategy in Experiment 1, even though the only difference was the instruction to remember the digit.

The last three experiments used perception of dichotic consonant-vowels as an indirect way to assess spatial bias. Participants were not asked to report on their perception of spatial features, but instead simply had to indicate which among four consonant-vowels they heard best on a given trial. The spatial component was inferred by which ear received the consonant-vowel that the participant reported hearing best on a given trial. Here again, with at least two small digits in memory information was biased toward the left side of space, which was shown by elimination of the typical right ear advantage. When larger digits were in memory the right ear advantage was comparable to what was seen in a control experiment (Experiment 4), as well as previous studies (Hugdahl, 2003; Yurgil & Golob, 2010). Future work could examine similarities and differences in the STM effects seen in each task, particularly because left/right judgments only examined one-digit loads (vs. 1–4 for dichotic listening). In addition, one perceptual judgment was given in each trial of left/right judgment, while four judgments (different consonant-vowels) were made in each trial in the dichotic listening experiments. Note that the present experiments all delivered memory items acoustically and measured auditory spatial judgments. Future work is needed to examine variables such as the sensory modality of memorized digits, item format (e.g., digits, words, or nonverbal items such as dots), and whether the spatial biases are limited to auditory space or have a multimodal influence on spatial judgments. Relations between encoding and retrieval cues, with respect to spatial bias, could also be examined (Golob & Starr, 2004b; Tulving & Thomson, 1973).

Dichotic listening uses an atypical stimulus, as sounds in the natural world are usually detected by both ears, and the brain makes inferences about auditory space by calculating differences between the ears (Stevens & Newman, 1936). Thus, the right ear advantage may be a peculiarity induced by unnatural dichotic sounds or, alternatively, could reflect true spatial processing. Many experiments have presented different stimuli from two speakers at the same time (e.g., Darwin et al., 1972; Getzmann et al., 2016), but the participant's task is usually to respond to targets rather than report which consonant-vowel they hear best. Two previous studies support a true spatial processing interpretation because a right ear advantage is evident when each consonant-vowel can be detected by both ears, either by defining location using small differences in sound onset time among ears (Morais & Bertelson, 1975) or by using two speakers in free-field (Morais, 1974; Morais & Bertelson, 1973). Indirect support is also provided by patients with high-level spatial attention deficits (hemineglect), who have atypical results when tested with various dichotic listening paradigms (Bellmann et al., 2001). Taken together, we cautiously conclude that self-reports using dichotic listening are likely to reflect true spatial coding for the sides of the constituent speech stimuli, but more work would be needed to strengthen this conclusion.

Short-Term Memory Load Effects

Experiment 2 showed that remembering one digit was sufficient to induce a left-right spatial bias on number magnitude when participants made direct judgments of left/right spatial location. In contrast, for the dichotic listening task at least two digits needed to be retained before there was a similar left/right numeric bias, and the effect of load across two to four items was not significant. The two tasks were substantially different in terms of the perceptual judgment (left/right spatial judgments vs. best perceived sound), stimulus type (nonverbal white noise vs. speech consonant-vowels), and stimulus complexity (one sound vs. a mixture of two sounds). The duration that number(s) had to be held in memory also differed between tasks (Experiment 2 = 2.5 s, Experiments 3–5 $\sim$20 s). Lastly, memory was tested using probe recognition in Experiment 2 while Experiments 3–5 used recall. Thus, we only offer a few speculations here that would require further study to validate.

The nature of the task (spatial vs. nonspatial judgment) could be important if the spatial codes associated with the digits are more likely to be influential when they relate to the explicit task requirements. Previous studies in visual search suggest such a distinction between task-relevant versus task-irrelevant information in STM (Olivers et al., 2011). When participants perform the dichotic listening task, which is an indirect metric of task-irrelevant spatial coding, greater memory load may be needed to have a spatial bias versus left/right judgment where space is relevant. According to load theory, the challenge of maintaining a task set increases with more items in memory (Lavie et al., 2004). Consequently, the chances of attending to representations that are not task-relevant, such as internal spatial codes associated with each number, could also increase (Chun et al., 2011). However, note that load theory would also predict that the numeric bias should increase with memory load, which was not seen here. The possibility that having several digits in a numeric range (e.g., smaller or larger) increases the salience of that class is also worth investigating.

The absence of a numeric spatial bias in Experiment 1 shows that presenting a number does not automatically influence subsequent spatial judgments. The effect of number magnitude was significant in Experiment 2 but not in Experiment 1. This difference among experiments was not due to results that happened to fall on either side of the $p < .05$ (alpha) dividing line for statistical significance. Indeed, the number bias effect size without memorizing the digits was $\eta_p^2 = .02$, yet was $\eta_p^2 = .33$ when the digits were memorized (>15-fold difference). We speculate that a fleeting numeric spatial code may require explicit encoding, and perhaps rehearsal, before it influences spatial judgments. However, under other circumstances passive presentation of numbers does show a priming effect on subsequent spatial judgments (Golob et al., 2016). One possibility drawn from the visual attention literature is that endogenous attention may be a more potent influence on perceptual qualities relative to exogenous cuing (Barbot & Carrasco, 2017; Prinzmetal et al., 2009). Thus, in Experiment 1 digits may have operated as an exogenous cue, but the need for memorization in Experiment 2 has similarities to endogenous cuing. Deeper, conceptual, processing can promote spatial cuing with visual numbers (Fischer et al., 2020); and processing was most likely deeper in Experiment 2 due to the memory requirement. Lastly, it may be worthwhile to attempt a replication to sort out these issues, particularly because spatial cuing effects from visual numbers have mixed results (Colling et al., 2020; Fischer et al., 2003, 2020; Zanolie & Pecher, 2014).

Mechanisms for Spatial Judgment Biases Induced by Digits in Short-Term Memory

A next step is to better understand the mechanisms for how a representation in STM can influence perception. Evidence from the left/right judgment and dichotic listening tasks both suggest that the numeric bias influences the left side of space. The number bias from a smaller number in memory on left/right judgments shifted the point of subjective equality (PSE) to the right, expanding left space, but did not pass beyond the true midline for larger numbers (see Figure 2). Similarly, remembering two or more smaller numbers reduced the right ear bias, and consequently boosted the likelihood of perceiving the consonant vowel on the left. However, large numbers in memory did not increase the right ear advantage beyond what is seen in nonmnemonic control conditions (Figures 4 and 5). A key question for future work is to distinguish whether STM information affects how basic features are coded, such as interaural level and perceived loudness, a location code derived from all three types of spatial cues, or a later stage of processing at the level of auditory objects which groups spatial and nonspatial information about a sound. Such granular information on relations between STM and perceptual features may help explain why the effect of memory load was mostly on the left side of space. Exploring connections between the present perceptual effects and the literature on mental number line literature may be fruitful. For example, variables such as reading direction differ among languages, and are associated with corresponding differences in spatial biases (Göbel et al., 2011).

Relevance to Mechanisms of Numeric Spatial Biases

This study provided new information about number biases on perception. As discussed in the Introduction, there is a large literature showing that number magnitude can affect performance, such as the speed of responding and accuracy (Hubbard et al., 2005). Our newer work supports the idea that number magnitude can also affect how people perceive stimuli, specifically by biasing the perceived location (Golob, Lewald, et al., 2017). The current study expands this line of work by showing that the spatial numeric bias persists when numeric information is retained in short term memory. This rules out a spatial bias resulting from a transient perceptual code only active during stimulus processing. The current results also expanded the generality of these left-right number biases, because they were also evident when making dichotic listening judgments of consonant vowels. Note that for dichotic listening the numeric bias was evident over 16 s trials and could have been susceptible to backward masking related to serial position (Crowder, 1978) or otherwise require an unfilled interval between memory encoding and the stimulus for spatial judgment. The durability of the spatial bias in dichotic listening is consistent with the idea that higher-level semantic and spatial codes used in STM are more likely mechanisms for the spatial bias rather than detailed perceptual codes, which are vulnerable to disruption by backward masking.

Observations that long-term knowledge about numbers affects low-level spatial judgments is consistent with theories of semantic memory where concepts include not only abstract representations of meaning but also, when applicable, representations of lower-level sensory features (Binder & Desai, 2011). Many cultures use a space-based ordering of numbers, such as a number line (Toomarian & Hubbard, 2018), which provides an opportunity to form spatial associations to the order and/or magnitude of numbers. Further work would be needed to determine whether the present findings reflect associations between numbers and space in long-term memory (Dehaene et al., 1993) or, instead, numeric order is represented in long-term memory and then acquires a spatial code when represented in STM (Abrahamse et al., 2016). Another possibility, which is not mutually exclusive to memory associations between number and space, is that a system for representing analog magnitudes is engaged when representing space, numbers, and time (Walsh, 2003). More work would be needed to explore these possibilities.

Mixed Number Effects

In the dichotic listening experiments, the finding that the laterality index was largest when there was a balanced mixture of larger and smaller numbers was unexpected. It is notable that the value of the laterality index is even greater than what is typically seen when participants intentionally attend to the right ear (Hugdahl et al., 2009). We are not aware of previous examples where an implicit bias is even larger than what is seen under explicit conditions. The main theories of why there is a right ear advantage focus on a privileged access of right ear stimuli to linguistic processing mediated by the left hemisphere (Kimura, 1967) or an attentional bias with similar effects (Hiscock & Kinsbourne, 2011; Kinsbourne, 1970). Neither one of these approaches can account for larger right ear advantages for mixed numbers in memory. For perspective, though, the STM number bias is novel with uncertain mechanisms, and is not the kind of data that these theories were designed to explain. Here we only offer a few speculations that would need rigorous testing.

We informally tested whether the range between digits in memory, that is, how many places in the ordering of digits were occupied by the largest and smallest digit in memory at one time, was associated with the laterality index (data not shown). The range between digits did not appear to account for the larger laterality index on mixed trials, but more formal work would be needed. Note that participants were not told that on some trials numbers would be grouped into a smaller (1–4) or larger (6–9) set of digits. Nonetheless, the majority of trials fit this pattern, which may have had an implicit strategic influence on responding.

Potential Influence of Eye Position

It is possible that eye position could be a mechanism for numeric bias in these experiments, particularly those using left/right judgments. Eye tracking was not monitored in the current project, and is thus a limitation. Myachykov and colleagues found differences in eye position for smaller versus larger numbers at latencies of ∼1,600 ms (∼2 pixels) and possibly 800 ms (Myachykov et al., 2015), with smaller numbers showing a drift in eye position farther to the left versus larger numbers. Small eye movements in the direction of memorized information when accessing working memory have also been observed (van Ede et al., 2019). There was a significant numeric memory bias in Experiment 2 but not in Experiment 1, which were identical except for digit memorization. This suggests that automatic shifts in eye position are unlikely to account for the STM bias on left/right judgments, although an ad hoc explanation is that encoding digits in Experiment 2 also induced eye movements systematically related to digit value. Eye position influences on sound localization typically have a bias in the opposite direction of the gaze (Lewald, 1998; Lewald & Ehrenstein, 1996; Lewald & Getzmann, 2006; Tabry et al., 2013); which would work against (underestimate) numeric spatial bias on left/right judgments. However, there are some reports of a spatial hearing bias in the same direction as the gaze (Cui et al., 2010; Razavi et al., 2007). Most relevant here, when using a left/right discrimination task similar to what was used in Experiments 1 and 2 there was no consistent eye-position bias on perceptual judgments (Experiment 1B in Lewald, 1997).

In summary, for the left/right judgment tasks we do not know whether systematic shifts in eye position as a function of digit value occurred. For the dichotic listening task used in Experiments 3–5 eye position is unlikely to have influenced the results because each consonant vowel is strongly lateralized to the right or left, and thus unlikely to be misperceived on the opposite side of midline. Perceptual fusion of the consonant-vowels would also be unaffected by such a small potential spatial bias of ∼2°. A previous study experimentally controlled eye movements before dichotic consonant-vowel stimuli, and the results were unaffected by left or right horizontal eye movements (Hiscock et al., 1985; Experiment 2). Lastly, we are not aware of a clear rationale for why eye position would influence the likelihood of finding large right ear advantages for mixed numbers and more intrusions when remembering smaller numbers.

Crosstalk and Functional Interpretation and Cognitive Penetration

Based on the current results, we do not suspect that there is a clear benefit to having number magnitude bias auditory spatial perception. It is challenging to make a case for how behavior would be improved by having a small spatial hearing bias as a function of number magnitude in memory. This subtle level of cognitive penetration, or conversely a failure to encapsulate, that is on the order of just noticeable differences, also distinguishes perceptual judgments of sounds triggered by one's actions versus those triggered by a different source such as a computer (Myers et al., 2020; Sato, 2008; Weiss et al., 2011). Instead, we propose that the number bias on spatial hearing in our experiments is likely a symptom of "crosstalk" in working memory. By "crosstalk" we mean that working memory for the digits recruited the same, or similar, spatial representations that are also used for perceptual judgments (Cohen, 2017). The impact of spatial code crosstalk on performance measures has been extensively studied in the Simon and spatial Stroop tasks (Chinn et al., 2018; Hommel, 2011; Lu & Proctor, 1995).

Evaluating the potential role of attention as a mechanism for how digits in memory influence spatial hearing is clearly an important question that is not addressed in the current study (Gross, 2017). The extent that attentional influences count as cognitive penetration is a current topic of debate (Firestone & Scholl, 2016; Gross, 2017; Montemayor & Haladjian, 2017). Another issue left unaddressed is whether the spatial biases from STM are present at earlier stages of perceptual processing, later decision stages, or at multiple time points between stimulus input and response output (Pylyshyn, 1999). This "time course" question is difficult to convincingly resolve using only behavioral measures but can be examined with direct measures of neural processing that have precise temporal resolution, such as EEG/MEG and intracranial recordings. Testing for convergent evidence by using methods that interfere with normal processing, such as transcranial magnetic stimulation, may also be helpful. Cognitive neuroscience approaches have contributed to understanding attentional mechanisms and may identify similar mechanisms in STM biases such as those reported in this article. This would be another line of attack for understanding questions of the relations among attention and working memory, which is a major distinction among theories of working memory (Baddeley, 2012; Miyake & Shah, 1999).

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