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Articulatory Suppression Impairs Working Memory for Ostensibly Unvocalizable Abstract
Sounds

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Abstract

Both subvocal articulatory rehearsal and attentional refreshing have been advanced as rehearsal mechanisms for verbal material (including speech sounds) in working memory, but the mechanism of rehearsal for nonverbal sounds—especially timbral attributes of sounds—remains unclear. Since timbral attributes of sounds often have been assumed to be unvocalizable, researchers have suggested that working memory for timbre must involve an attentional or sensory (rather than subvocal) maintenance mechanism. Two experiments examined the role of subvocal rehearsal and attentional refreshing in working memory for timbre using sounds that were designed to be abstract, unvocalizable, and devoid of apparent mnemonic semantic connections. Participants heard either three (Experiment 1) or two (Experiment 2) brief (250 ms), abstract sounds. Following an 8000 ms retention interval, participants heard a single probe sound and indicated whether the probe had been a member of the original set. During the retention interval, manipulations were introduced to suppress subvocal articulatory rehearsal, attentional refreshing, or both. Across both experiments, all conditions with articulatory suppression during the retention interval showed worse memory performance than a control condition. Effects of attentional refreshing suppression were inconsistent. These experiments suggested that subvocal imitation may be an important mechanism of rehearsal in working memory for timbre—a finding that presents complications for existing theoretical perspectives on both verbal and nonverbal working memory.

Articulatory Suppression Impairs Working Memory for Ostensibly Unvocalizable Abstract Sounds

Working memory is a construct that is generally defined to encompass active cognitive processes, including the temporary storage, activation, and manipulation of information (see, e.g., Logie & Cowan, 2015). Models of working memory commonly have attempted to explain mechanisms of active rehearsal of information in working memory, which in part has led to theories positing the fractionation of working memory into domain-specific processes (Miyake & Shah, 1999). For example, Baddeley's model of working memory (see Baddeley, 2012) differentiated phonological working memory processes from visual and spatial working memory processes by specifying distinct mechanisms for different types of information (i.e., a *phonological loop* for verbal information and a *visuospatial sketchpad* for visual and spatial information).

A great deal of research has examined working memory for verbal auditory stimuli (i.e., speech sounds and linguistic information) in the context of Baddeley's phonological loop (for reviews, see Baddeley, 2003, 2012), which was comprised of two subcomponents: a subvocal rehearsal mechanism and a brief duration phonological store. Evidence in support of subvocalization as an important verbal rehearsal mechanism has come from research paradigms using *articulatory suppression*. Articulatory suppression entails requiring participants to vocalize (or to covertly subvocalize) task-irrelevant materials (repeating "the," counting aloud, etc.) during retention of to-be-remembered verbal materials. Articulatory suppression has been shown to disrupt the subvocal rehearsal mechanism of verbal working memory and thereby to impair memory for verbal materials (e.g., serial lists of letters or numbers) (see, e.g., Baddeley, Lewis, & Vallar, 1984; Belleville, Peretz, & Arguin, 1992; Larsen & Baddeley, 2003).

Fewer studies have examined working memory for nonverbal auditory stimuli (e.g.,

sounds that are not the sounds of human language, such as tones, music, and environmental sounds), and the theoretical mechanism of rehearsal for nonverbal sounds is not clear. Baddeley and Logie (1992) suggested that the phonological loop might accomplish auditory imagery—a function typically attributed to working memory (see Logie & Cowan, 2015)—for nonverbal sounds. In this case, subvocalization presumably would be the mechanism of working memory rehearsal for both verbal and nonverbal sounds, and nonverbal sounds would be rehearsed by using subvocalization to imitate the acoustic properties of sounds. Others, however, have argued that some aspects of nonverbal sounds, especially perceptual characteristics typically described as *timbre*¹, must involve “sensory rather than motor imagery” (Crowder, 1989, p. 478) on the grounds that timbral attributes of sounds cannot be accurately imitated with the human vocal apparatus. Similarly, Berz (1995) suggested that musical sounds are rehearsed in a specialized *musical memory loop* in working memory that is distinct from the phonological loop.

If verbal and nonverbal auditory stimuli are maintained in working memory by different mechanisms, then articulatory suppression—a procedure that interferes with the subvocal rehearsal mechanism of verbal working memory—should have little effect on working memory for nonverbal sounds. Research to examine the effects of articulatory suppression on nonverbal musical sounds, however, often has shown that articulatory suppression does impair memory for those sounds. For example, across multiple studies, articulatory suppression has been shown to impair memory for melodies (Logie & Edworthy, 1986; Nees, Corrini, Leong, & Harris, 2017; Schendel & Palmer, 2007). Articulatory suppression also has been shown to interfere with other musical tasks that seem to have a nonverbal memory component, including judging the pitch content of recognizable melodies (Smith, Wilson, & Reisberg, 1995) and judging differences

¹ *Timbre* is a term that has been fraught with definitional problems (Siedenburg & McAdams, 2017a). In this manuscript, we use the term to refer to the perceptual attribute of sounds that allows for sounds to be discriminable when pitch, loudness, and spatial location are held constant.

between musical notation and heard melodies (Brodsky, Kessler, Rubinstein, Ginsborg, & Henik, 2008).

Still, the detrimental effects of articulatory suppression on memory for musical sounds has not been consistent in published findings, particularly when experimental tasks involved memory for the timbre of sounds rather than pitch or pitch changes. Halpern, Zatorre, Bouffard, and Johnson (2004) claimed that "...although subvocalizing the timbre of an instrument is difficult, the timbre [in their experiment] was accompanied by pitch, which itself is easily vocalizable" (p. 1291). From this perspective, the pitch of nonverbal sounds can be rehearsed via subvocalization in working memory, whereas rehearsal of timbral attributes of nonverbal sounds requires a different mechanism (also see Crowder, 1989; Soemer & Saito, 2015). Recent research (e.g., Lemaitre, Dessein, Susini, & Aura, 2011), however, has suggested that people can approximate many nonverbal sounds, including some timbral aspects of sounds (Lemaitre, Jabbari, Houix, Misdariis, & Susini, 2015), with vocal imitations. Still, researchers have continued to express skepticism regarding the potential role of subvocal imitation in rehearsal of nonverbal sounds in working memory, particularly for sounds discriminable primarily by timbre differences (e.g., Golubock & Janata, 2013; Li, Cowan, & Saults, 2013; Schulze, Koelsch, & Williamson, 2018).

Three recent studies have examined the effects of articulatory suppression on sounds that were synthesized to be discriminable by timbre and not pitch. Schulze and Tillmann (2013) found no effect of articulatory suppression on memory for sounds discriminable by timbre. Soemer and Saito (2015) likewise found that articulatory suppression did not interfere with timbre memory for sequences of three or four sounds, but articulatory suppression did negatively impact memory performance with two-sound sets. Using a similar procedure, however, Siedenburger and McAdams (2017b) found a negative impact of articulatory suppression on timbre

memory for sequences of three sounds. They suggested that articulatory suppression impaired memory for timbre by interfering with the auditory memory trace (rather than the working memory rehearsal mechanism for timbre). Siedenburg and McAdams further observed that a visual distractor task also negatively affected timbre memory—a finding which led them to speculate that *attentional refreshing* may play an important role in maintaining and rehearsing timbre in memory.

Attentional refreshing has been defined as “the act of turning one’s focus of attention to a representation, thereby augmenting its accessibility in [working memory]” (Souza, Rerko, & Oberauer, 2015, p. 20). Camos, Lagner, and Barrouillet (2009) suggested that subvocalization and attentional refreshing can operate concurrently and independently to maintain the same information in verbal working memory. Whereas subvocalization is generally regarded as a domain-specific process that places minimal demands on attention (e.g., Naveh-Benjamin & Jonides, 1984), attentional refreshing is a domain-general process. As such, subvocalization can be interrupted only by a narrow range of concurrent tasks (articulatory suppression, etc.), whereas any concurrent task that requires attention should disrupt maintenance that depends on attentional refreshing in working memory.

Nees, Corrini, et al. (2017) examined the respective roles of subvocalization and attentional refreshing in working memory rehearsal for brief four-note melodies. The melodies were followed by a retention interval, after which participants heard a probe sound and indicated whether the probe had been a note in the original melody. Their procedure introduced manipulations during the retention interval to suppress: (1) articulation; (2) attentional refreshing; or (3) both articulation and attentional refreshing. In the articulatory suppression condition, participants viewed simple math problems that already were solved (e.g., “ $4 - 1 = 3$ ”) and read the problems aloud, whereas the condition to suppress both articulation and attentional

refreshing required participants to read aloud and solve unworked problems (e.g., “ $4 - 1 = ?$ ”). Both conditions were modeled on the procedure used in Camos et al. (2009, Experiment 1). The vocalization requirement of the former condition suppressed subvocalization of to-be-remembered stimuli; the requirement to solve the problems in the latter condition imposed additional demands on attention. Nees et al. introduced a fourth condition to selectively interfere with attentional refreshing: participants silently viewed unsolved math problems and solved the problems by pressing a number on a computer keyboard. This condition was intended to impose the attentional demand of solving the problem without suppressing subvocal rehearsal of the melodies. Results showed that both conditions with articulatory suppression impaired memory performance as compared to a control condition and the condition with only attentional refreshing suppression, which were not different from each other. The results suggested that subvocal rehearsal plays a role in maintenance of memory for melodies, whereas attentional refreshing does not. Because the melody stimuli were discriminable by changes in pitch, however, these findings did not rule out the possibility that attentional refreshing plays a role in memory for the timbre of nonverbal stimuli.

On the whole, then, experiments have mostly shown that concurrent articulation of unrelated material interferes with maintenance of to-be-remembered nonverbal stimuli—such as melodies—when those stimuli are discriminable by pitch (Brodsky et al., 2008; Koelsch et al., 2009; Li et al., 2013; Logie & Edworthy, 1986; Nees, Corrini, et al., 2017; Schendel & Palmer, 2007). In studies of memory for timbre—in which pitch information does not aid the memory task—the effects of articulatory suppression have been inconsistent. Two studies (Schulze & Tillmann, 2013; Soemer & Saito, 2015) showed that articulatory suppression did not interfere with memory for timbre, whereas a third study (Siedenburg & McAdams, 2017b, Experiment 2) did find effects of articulatory suppression. Pitch has been described as vocally imitable, whereas

timbre has been described as difficult or impossible to subvocalize (Crowder, 1989; Halpern et al., 2004). As such, it has been suggested that subvocalization may be useful for working memory rehearsal of pitch, but not timbre (Soemer & Saito, 2015), and attentional refreshing has been proposed to be an important process for rehearsal of timbre in working memory (Siedenburg & McAdams, 2017b).

Current Studies

The current studies sought to examine subvocalization versus attentional refreshing as potential mechanisms of rehearsal for timbre in working memory. In a study of the capacity of nonverbal auditory working memory, Golubock and Janata (2013, Experiment 1) synthesized sound stimuli that were designed to be abstract, purportedly non-verbalizable (i.e., unvocalizable) sounds that were discriminable by timbral characteristics alone. The Golubock and Janata sounds were chosen for use in the current research, because the sounds were designed to be particularly challenging to rehearse using subvocalization and were not discriminable using pitch cues. If timbre is not subvocalizable (e.g., Crowder, 1989; Halpern et al., 2004; Soemer & Saito, 2015) and different rehearsal strategies (e.g., attentional refreshing) are used to maintain timbre in working memory, then the abstract sounds used here should require those non-subvocal rehearsal strategies.

In the current experiments, both of which were approved by the Lafayette College Institutional Review Board, participants heard a sequence of either three (Experiment 1) or two (Experiment 2) abstract sounds. Following an 8000 ms retention interval, participants heard a single probe sound and indicated whether it had been part of the original sequence. During the retention interval, tasks to suppress articulatory rehearsal, attentional refreshing, or both, were compared to each other and to a control condition. If working memory for timbre does not involve subvocal rehearsal, then articulatory suppression should have little effect on memory for

the sounds used in these experiments. Further, if attentional refreshing plays a role in maintenance of timbre in working memory, then suppression of attentional refreshing should impair memory for the sounds used in these experiments. If both mechanisms contribute to working memory rehearsal for these sounds, then conditions with suppression of both articulation and attentional refreshing during the retention interval should exhibit the worst performance of all conditions on the memory task.

Experiment 1: Memory for Three-sound Sequences

Methods

Participants. Participants ($N = 81$, 60 females, M age = 19.04 years, $SD = .87$) were recruited from undergraduate psychology courses at Lafayette College and were compensated with course extra credit. Participants reported means of 3.90 years of experience playing a musical instrument ($SD = 4.23$, $mdn = 3.00$, mode = 0), 2.95 years of experience reading musical notation ($SD = 4.16$, $mdn = 1.00$, mode = 0), and 3.43 years of formal musical training ($SD = 3.69$, $mdn = 2.00$, mode = 0). Participants' self-reported musical ability was a mean of 2.96 ($SD = 1.59$, $mdn = 3.00$, mode = 2), on a scale from 1 ("I have no musical ability at all") to 7 ("I am a professional musician").

Sound Stimuli. The sounds used in this study were created by Golubock and Janata, (2013, Experiment 1), who synthesized a set of stimuli with the goal of producing abstract sounds with no semantic associations that are not verbalizable. Each sound began with a fundamental frequency of 331 Hz with 19 harmonics. Golubock and Janata used MATLAB functions to manipulate the attack (rise time and amplitude envelope), spectral centroid (weighting of the 20 partials), and spectral flux (involving amplitude and frequency modulation of the partials) of the sounds. The stimuli were normalized with respect to perceived loudness. These manipulations defined a three-dimensional timbre space (see their Figure 2) whose sounds

were subjected to extensive listener testing to examine their discriminability. We used only the eight corner stimuli from their timbre space in this study, because their listener tests indicated that these eight sounds were clearly discriminable from one another. Each sound used had a duration of 250 ms. The main manuscript and supplemental materials in Golubock and Janata give a detailed description of the stimulus creation and testing procedure.

Math problems. A website (www.mathfactscafe.com) was used to randomly generate simple math problems that required addition or subtraction of two numbers. Constituent members of the problems and solutions were constrained to the digits 1-9, and a set of 96 problems was generated for the study.

Apparatus. The main experiment was coded in a Flash program that was embedded in a Qualtrics survey. Visual presentations were made in a browser running on a 21.5 inch iMac computer. Sounds were presented through Bose Companion II desktop speakers positioned to each side of the monitor approximately 30 inches from the participant's ears.

Timbre Memory Task. On a study trial, participants heard a random selection (without replacement) of three of the eight sound stimuli. A pilot study (see supplemental materials) had suggested a ceiling effect with only one sound, so three sounds were chosen to impose more demands on memory. Sounds were separated by 100 ms inter-stimulus intervals. This standard three-sound stimulus set was followed by an 8000 ms retention interval, after which participants heard a single probe sound. Their task was to indicate whether the probe was a member of the initial standard stimulus set. Responses were made by clicking a button with the computer mouse. Within each condition, there were 16 total trials of the timbre memory task. For half of trials in each condition, the probe matched one of the sounds in the standard set. Half of those match trials used a probe that matched the second sound in the standard stimulus sequence, and half matched the third sound in the standard stimulus sequence. Non-matching probes were

randomly selected for each trial. The order of trials for the different types of probes (non-matching, matching with the second sound, or matching with the third sound) was randomly determined for each condition for each participant. A mandatory 5000 ms pause was implemented between trials after a response was logged.

Experimental Conditions. Four different manipulations were introduced during the 8000 ms retention interval. In the control condition, the retention interval was empty (i.e., participants saw a white screen). In the articulatory suppression (AS) condition, participants viewed solved math problems (e.g., “ $5 - 1 = 4$ ”) during the retention interval and were instructed to read the problems aloud (e.g., by saying “five minus one equals four”) at a fast, consistent pace and a normal conversational volume. Participants saw two math problems during the retention interval. The first problem appeared on the screen for 3200 ms immediately following the offset of the last sound in the standard stimulus set. Following an 800 ms empty inter-stimulus interval, the second math problem appeared for 3200 ms. Another 800 ms empty inter-stimulus interval separated the offset of the last math problem and the onset of the probe sound. For each trial, the math problems were randomly selected without replacement from the set of 96 problems. In the condition with both articulatory suppression and attentional refreshing suppression (AS+ARS), trials were the same except that participants viewed unsolved math problems (e.g., “ $5 - 1 = ?$ ”) and were instructed to solve the problems as they read them aloud. In past research (Camos et al., 2009; Nees, Corrini, et al., 2017), reading already-solved problems during retention intervals has been used to suppress articulatory rehearsal, but not attentional resources, whereas reading and solving problems suppresses the use of both articulatory rehearsal and attention to aid maintenance of the to-be-remembered stimuli. In the condition with only attentional refreshing suppression (ARS), participants silently viewed unsolved math

problems and gave answers by pressing keys on the computer keyboard without speaking the problems aloud (see Nees et al., 2017).

Procedure. After informed consent, participants were seated in front of a computer in a private testing room. At the beginning of the experimental procedure, the experimenter played all eight sounds for participants to hear. Next, the four experimental conditions were completed. The order of conditions was randomly determined for each participant. An experimenter sat in the testing room behind participants during all experimental procedures to confirm that they understood the instructions for each condition, which were given in the Flash program. The experimenter also observed to verify that participants followed instructions for conditions with articulatory suppression. Lastly, the experimenter collected data regarding participants' accuracy in solving the math problems in conditions with attentional refreshing suppression. After finishing experimental trials for all conditions, participants answered demographic questions.

Results

Measures of sensitivity (d') were calculated as the primary dependent variable. Since hit rates and false alarm rates of 0 and 1.00 are impermissible in signal detection analyses, hit rates and false alarm rates of 0 and 1.00 were replaced with rates of .0625 ($0.5 \div n$, where n was the number of potential hits or false alarms) and .9375 [$(n - 0.5) \div n$], respectively (see Stanislaw & Todorov, 1999). Two participants (from an original sample of $N = 83$) provided data points that were outliers, operationally defined here as a d' score that exceeded ± 3 SDs from the group mean in at least one condition. The first participant had a d' score of 3.07 in the AS+ARS condition ($N = 83$ group $M = 0.76$, $SD = .70$) and had d' scores of 0.48, -0.32, and 0.00 in the other three conditions. The second participant had a d' score of -1.35 in the ARS condition ($N = 83$ group $M = 0.94$, $SD = 0.58$) and logged scores of 0.67, 1.82, and 0.99, in the other three conditions, respectively. For both participants, we believed that the deviation of the outlier scores

from both (1) the rest of the sample's performance in the conditions for which the participants were outliers; and (2) the participants' own performance in other conditions of the experiment; suggested that an aberrant process had produced the scores, so the participants were removed from all further analyses.

A 1x4 repeated measures analysis was conducted to allow for comparison of all conditions to each other and the control condition. Mauchly's Test indicated that the assumption of sphericity was violated, $\chi^2(5) = 13.41, p = .02$, so a Greenhouse-Geisser correction was used. Fisher's LSD test was used for all post hoc comparisons. A 1 x 4 repeated measures analysis of variance (ANOVA) showed a significant effect of condition on d' scores, $F(2.72, 217.95) = 5.02, p = .003, \eta_p^2 = .06$. Pairwise comparisons revealed that, as compared to the control condition ($M = .99, SE = .09$), participants demonstrated worse performance in the AS condition ($M = .67, SE = .08$), $p = .008$, and the AS+ARS condition ($M = .73, SE = .07$), $p = .03$, which were not significantly different from each other, $p = .57$. Participants also performed worse in the AS and AS+ARS conditions than in the ARS condition ($M = .98, SE = .06$), $ps = .002$ and $.01$, respectively. The control and ARS conditions were not significantly different, $p = .92$. Results are shown in Figure 1.

Figure 1. Mean sensitivity scores in Experiment 1. Error bars represent standard error.

Mistakes per participant on the math problems in the ARS ($M = .35$, $mdn = 0$, $mode = 0$) and the AS+ARS ($M = .15$, $mdn = 0$, $mode = 0$) conditions were rare. Spearman's rho was used to look for evidence of a relationship that would suggest a trade-off in performance occurred between math mistakes and d' scores, but no relationship was found for either the ARS condition, $r_s(79) = .03$, $p = .40$, or the AS+ARS condition, $r_s(79) = -.10$, $p = .19$.

Exploratory Analysis. An exploratory analysis was run to compare d' scores for trials in which the probe sound matched the second versus the third sound in the sequence ($n = 16$ trials of each; 4 trials of each per condition). This analysis was collapsed across the manipulations during the retention interval. A two-tailed, dependent samples t-test showed that performance was not significantly different when the probe stimulus was in the second ($M = .75$, $SE = .06$) versus third ($M = .89$, $SE = .05$) position in the sequence, $t(80) = -1.91$, $p = .06$.

Discussion

Both conditions that featured AS during the retention interval showed worse memory performance than a control condition and a condition that featured only ARS. Further, memory performance in the ARS condition was not different from the control condition, and the AS+ARS condition did not result in worse performance than AS alone. Taken together, the results suggested that subvocal articulatory rehearsal plays a role in working memory for nonverbal sounds discriminable only by timbre, whereas attentional refreshing does not. The results mirrored the pattern of findings for memory for melodies reported in Nees, Corrini, et al. (2017), which lends some support to the hypothesis that pitch and timbre share a rehearsal mechanism in working memory.

Across all conditions, the d' scores were relatively low. Some participants recorded

negative d' scores (which were analyzed as such) in some conditions, which indicated the memory task was difficult or nearly impossible in those instances. A pilot study had suggested that the task was too easy with just one standard sound (see the supplemental materials), but Experiment 1 showed the task was difficult with three standard sounds. To confirm that the pattern of results was robust, we conducted a second experiment to replicate the procedure with two standard sounds.

Experiment 2: Memory for Two-sound Sequences

Method

Participants. Participants ($N = 79$, 63 females, M age = 19.20 years, $SD = 1.13$) were recruited from undergraduate psychology courses at Lafayette College and were compensated with course extra credit. Participants reported means of 4.52 years of experience playing a musical instrument ($SD = 4.72$, $mdn = 4.00$, mode = 0), 4.39 years of experience reading musical notation ($SD = 4.87$, $mdn = 3.00$, mode = 0), and 4.29 years of formal musical training ($SD = 4.30$, $mdn = 3.00$, mode = 0). Participants' self-reported musical ability was a mean of 3.05 ($SD = 1.60$, $mdn = 3.00$, mode = 1.00), on a scale from 1 ("I have no musical ability at all") to 7 ("I am a professional musician").

Stimuli, Task, Experimental Conditions, and Procedure. The stimuli, task, experimental conditions, and procedure in Experiment 2 were the same as in Experiment 1, except that the initial standard sound sequence used two sounds instead of three. As in Experiment 1, the standard sounds were separated by a 100 ms inter-stimulus interval. The retention interval of 8000 ms began with the offset of the second sound. For trials in which the probe sound was a match, half of the probes matched the first sound and half matched the second sound in the standard stimulus sequence.

Results

Using the same operational definition as Experiment 1, one participant (from an original sample of $N = 80$) provided a data point that was an outlier. The participant had a d' score of -0.67 in the ARS condition ($N = 80$ group $M = 1.37$, $SD = 0.67$) and had d' scores of 1.82 , 0.99 , and 1.35 in the other three conditions. We believed that the deviation of the outlier score from both (1) the rest of the sample's performance in the condition for which the participant was an outlier; and (2) the participants' own performance in other conditions of the experiment; suggested that an aberrant process had produced the score, so the participant was removed from all further analyses.

Mauchly's Test indicated that the assumption of sphericity was met, $X^2(5) = 4.10$, $p = .54$. Fisher's LSD test was used for all post hoc comparisons. A 1×4 repeated measures analysis of variance (ANOVA) showed a significant effect of condition on d' scores, $F(3, 234) = 9.55$, $p < .001$, $\eta_p^2 = .11$. Pairwise comparisons revealed that, as compared to the control condition ($M = 1.63$, $SE = .09$), participants demonstrated worse performance in the AS condition ($M = 1.22$, $SE = .08$), $p < .001$, the AS+ARS condition ($M = 1.12$, $SE = .09$), $p < .001$, and the ARS condition ($M = 1.39$, $SE = .07$), $p = .01$. The AS condition was not significantly different from AS+ARS condition, $p = .35$, or the ARS condition, $p = .09$, but participants performed significantly worse in the AS+ARS condition as compared to the ARS condition, $p = .01$. Results are shown in Figure 2.

Figure 2. Mean sensitivity scores in Experiment 3. Error bars represent standard error.

Mistakes per participant on the math problems in the ARS ($M = .14$, $mdn = 0$, $mode = 0$) and the AS+ARS ($M = .09$, $mdn = 0$, $mode = 0$) conditions were rare. Spearman's rho was used to look for evidence of a relationship that would suggest a trade-off in performance between math mistakes and d' scores, but no relationship was found for either the ARS condition, $r_s(77) = -.06$, $p = .31$, or the AS+ARS condition, $r_s(77) = -.10$, $p = .19$.

Exploratory Analysis. An exploratory analysis was run to compare d' scores for trials in which the probe sound matched the first versus the second sound in the sequence ($n = 16$ trials of each; 4 trials of each per condition). This analysis was collapsed across the manipulations during the retention interval. A dependent samples t-test showed no significant difference when the probe stimulus was in the first ($M = 1.38$, $SE = .07$) versus second ($M = 1.33$, $SE = .06$) position in the sequence, $t(78) = 0.56$, $p = .58$.

Discussion

Like in Experiment 1, both conditions that required articulatory suppression resulted in significantly worse performance than the control condition, and attentional refreshing suppression paired with articulatory suppression did not result in worse performance than articulatory suppression alone. This pattern of findings continued to suggest that articulatory rehearsal plays a role in memory for nonverbal sounds discriminable only by timbre. In Experiment 2, however, attentional refreshing suppression resulted in worse performance than the control condition and was not significantly different from the articulatory suppression condition. Whereas Experiment 1 provided no evidence of a role for attentional refreshing in memory for timbre, the results of Experiment 2 suggested that attentional refreshing might also be involved in maintenance of nonverbal sounds in memory.

General Discussion

Across two experiments, we found that articulatory suppression during a retention interval impaired memory for nonverbal sounds that were discriminable by timbre and were not vocalizable (at least ostensibly) or amenable to rehearsal aided by semantic mnemonics. Suppression of attentional refreshing significantly impaired memory as compared to a control condition only in Experiment 2. Subvocal rehearsal and attentional refreshing have been proposed to work concurrently and independently to maintain information in verbal working memory. With to-be-remembered verbal materials, Camos et al. (2009) showed a significant working memory decrement in a condition requiring articulatory suppression plus attentional refreshing suppression as compared to articulatory suppression alone. With nonverbal sounds, however, we found that pairing attentional refreshing concurrently with articulatory suppression produced no effect beyond that of articulatory suppression alone. Our experiments also produced findings that were different from some previous studies of the effects of articulatory suppression on working memory for timbre.

Discrepancies with Previous Experiments

At least two experiments (Schulze & Tillmann, 2013; Soemer & Saito, 2015) have found that articulatory suppression did not interfere with memory for timbre, whereas the current studies and another (Siedenburg & McAdams, 2017b, Experiment 2) did find effects of articulatory suppression. A possible explanation of the different results across studies is methodological. Schulze and Tillman used a retention interval of 3 seconds, as did one condition in Soemer and Saito. Siedenburg and McAdams used a retention interval of 6 seconds, and the current studies used a retention interval of 8 seconds. Auditory sensory memory—a construct that is distinct from working memory—persists for an indeterminate amount of time following auditory sensation and operates in parallel with working memory rehearsal, so shorter retention intervals may be more prone to capture influences of sensory memory rather than

rehearsal in working memory (Nees, 2016). More research is needed to definitively resolve the discrepancies in results across studies, but a consideration of the possible confounding of working memory with sensory memory at shorter retention intervals seems warranted. A better understanding of the relationship between working memory and sensory memory will be required for any complete theoretical explanation of auditory working memory.

Variability in Rehearsal Strategies

The results reported here also should be considered in the context of potential inter- and intra-individual variability in working memory rehearsal strategies. Previous research (Nees & Best, 2013; Nees & Walker, 2013) has suggested that people can follow prescriptions (i.e., during task instructions) to flexibly encode sounds according to a number of different strategies, including verbal labeling, visual imagery, and encoding of sounds as sounds per se. We recently examined self-reported spontaneous encoding strategies for both tonal and timbral stimuli (i.e., the sounds used in this study) (Nees, Harris, & Leong, 2017). This analysis showed that people introspectively report using a variety of strategies to remember timbres, including verbal labeling, remembering the sounds as sounds per se, and associating the sounds with existing information in long-term memory (using mnemonics, etc.). Working memory rehearsal is likely characterized by individual differences in strategies, and those differences in strategies can be obscured by nomothetic approaches that examine average differences across conditions. In this case, significant differences in means (like those observed here) may reflect the modal or typical default rehearsal strategy used by participants; less common strategies may not be evident in the group data (see, e.g., Mathews, Hunt, & MacLeod, 1980).

Theoretical Implications

The pattern of results in these experiments suggested at least two possibilities: (1) subvocalization is a working memory rehearsal mechanisms for sounds discriminable only by

timbre and whose distinguishing perceptual characteristics seem difficult to accurately vocalize; or (2) subvocalization, while not a rehearsal mechanism for nonverbal sounds, impairs memory for nonverbal sounds by interfering with a non-rehearsal component of the working memory process.

The first possibility—that subvocal rehearsal is used to maintain timbre in working memory—seems to entail that nonverbal sounds are rehearsed in working memory using subvocal imitations of perceived acoustic properties of sounds. Of note, spontaneous imitation of the acoustic characteristics of heard speech sounds has been documented (e.g., Pardo, 2006), so it is perhaps not a leap to suggest that the same occurs for nonverbal sounds. The notion that subvocalization aids memory for timbre has previously been rejected on the grounds that timbral properties of sounds are not vocalizable (e.g., Crowder, 1989), though that justification was assumed and not tested. Lemaitre et al. (2011) showed that people produce at least modestly accurate vocal imitations of many common everyday sounds. In their study, participants' recorded vocalizations were effective enough that a new sample of participants could sort the sound sources into broad categories, though imitations of liquid sounds were especially challenging. Further, Pfordresher, Brown, Meier, Belyk, and Liotti, (2010) showed that non-musicians could imitate unfamiliar melodies mostly accurately, though somewhat imprecisely.

To account for rehearsal in working memory, subvocal imitations of nonverbal sounds—including sounds discriminable only by timbre—would not necessarily need to be particularly accurate. Subvocal rehearsal of nonspeech sounds—even timbres—may not require that people produce veridical imitations of timbre, but the imitation would need to be unique for each unique item retained in working memory (Smith, Reisberg, & Wilson, 1992). Indeed, Lemaitre and colleagues have shown that participants' vocal imitations of nonverbal sounds tend to accentuate the salient vocalizable features of the sounds—an approach that is different from attempting to

faithfully mimic the acoustic signal (Lemaitre, Houix, Voisin, Misdariis, & Susini, 2016; Lemaitre et al., 2015). A consequence of less accurate imitation of nonverbal (as compared to speech) sounds presumably would be that those sounds are more difficult than verbal sounds to rehearse in working memory, which would result in worse memory for nonverbal sounds. Research indeed has shown that tones (Li et al., 2013), synthesized timbres (Golubock & Janata, 2013), and environmental sounds (Philipchalk & Rowe, 1971; Rowe & Rowe, 1976) typically are not remembered as well as verbal information.

If subvocalization is the rehearsal mechanism for timbre in working memory, the theoretical implications could be far-reaching. Since subvocalization already has been implicated in working memory rehearsal for speech sounds and nonverbal pitch, the current results regarding timbre suggested that subvocalization may offer a parsimonious explanation of working memory rehearsal for all sounds. This proposition, however, presents complications for extant theories of verbal working memory and even speech perception. For example, this conclusion would seem to lend support to arguments that the “phonological loop” (see Baddeley, 2012) is not, in fact, “phonological.” Jones and colleagues (Jones, Hughes, & Macken, 2006; Jones, Macken, & Nicholls, 2004) have argued that verbal working memory is a function of auditory sensory memory coupled with an articulatory (but not phonological) rehearsal mechanism. By definition, phonological representation requires abstraction that reduces percepts into a smaller number of discrete categories—usually the phonemes of language. Phonological representation is neither articulatory nor auditory, but instead uses “‘central’ representations that are functionally remote from more peripheral perceptual or motoric systems” (Jones et al., 2006, p. 266). Since nonverbal sounds are not part of the phonological corpus, the conclusion that verbal and nonverbal sounds share a subvocal rehearsal process in working memory would seem to support Jones and colleagues’ non-phonological view of working memory rehearsal. Further,

encoding of nonverbal sounds via subvocal imitation also would seem to present challenges for perspectives (e.g., the Motor Theory of speech perception, see Liberman & Mattingly, 1985) positing that speech sounds activate a special perceptual processing module via their status as vocalizable sounds (for a related perspective, see Schulze, Vargha-Khadem, & Mishkin, 2012).

Our results cannot rule out the possibility, however, that articulatory suppression interfered with memory for nonverbal sounds in our experiments via some mechanism that does not involve suppression of active rehearsal per se of nonverbal sounds. Siedenburg and McAdams (2017b) suggested that articulatory suppression might interfere with working memory for timbre by disrupting auditory sensory memory or occupying attentional resources.

The suggestion that articulatory suppression interferes with the auditory trace presumably refers to the possibility that the sound of one's own voice during articulatory suppression interferes with auditory sensory memory for the to-be-remembered sounds. This possibility, however, has been examined and ruled out in studies of both verbal (Macken & Jones, 1995) and nonverbal (Nees, Corrini, et al., 2017) materials. For example, Nees et al. showed that both overt (aloud) and silent (mouthed) articulatory suppression impaired memory for melodies. Neuroscience research has shown that the sound of one's own voice is perceptually attenuated during self-generated speech (e.g., Greenlee et al., 2011), which suggests that one's own voice may have limited ability to produce acoustic interference. Collectively, these findings have shown that an appeal to auditory interference from the sound of one's own voice cannot explain the detrimental effects of articulatory suppression on memory for sounds.

Although attentional refreshing also has been proposed as a theoretical mechanism to maintain timbre in working memory (Siedenburg & McAdams, 2017b), the current studies found inconsistent effects of attentional refreshing suppression on memory for abstract nonverbal sounds. In both studies, suppression of attentional refreshing in concert with articulatory

suppression did not result in worse performance than articulatory suppression alone, which is different from results obtained using a similar procedure with verbal materials (Camos et al., 2009). Experiment 1 offered no evidence that suppressing attentional refreshing impaired memory, whereas Experiment 2 showed that attentional refreshing suppression resulted in worse memory performance than the control condition. More research is needed to explain this discrepancy. Recent research (Lim, Wöstmann, Geweke, & Obleser, 2018), for example, showed that the effectiveness of attentional refreshing was contingent upon the interplay of task loads and individual differences in working memory capacity for syllables. Our Experiment 2 and Experiment 1 seemed to differ in task difficulty (and thus the cognitive load imposed), so further examinations of attentional refreshing across different cognitive loads may offer a useful avenue for future research. Although the results of Experiment 2 make it difficult to entirely rule out a role for attentional refreshing in memory for timbre, the overall patterns of results across these studies suggested that its role, if any, might be ancillary or supplementary to subvocal rehearsal, at least with respect to the modal or typical default rehearsal strategy across participants.

Conclusions

Two experiments showed that articulatory suppression impaired memory for abstract, nonverbal sounds that were designed to be distinguishable only by their timbral differences and difficult to vocalize. Taken together, the results of this study and others (Nees, Corrini, et al., 2017) have suggested that rehearsal of nonverbal sounds in working memory may rely on subvocal processes, or at least be subject to interference from concurrent subvocalization—a finding that is not readily explained by existing theoretical accounts of auditory cognition. Although attentional refreshing has been posited to play a role in rehearsing timbral characteristics of sound in working memory, we found inconsistent effects of suppression of

attentional refreshing rehearsal. A complete theoretical account of auditory working memory must explain how articulatory suppression interferes with memory for sounds that, at least ostensibly, cannot be vocalized. A candidate solution is that working memory rehearsal for timbre involves subvocal imitation of salient acoustic properties of the sounds, even when the distinguishing features of the sounds are difficult or impossible to vocalize accurately.

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