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Can vibrotactile working memory store multiple items?

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ABSTRACT

Vibrotactile working memory is increasing in popularity as a model system to test theories of working memory. Notably, however, we know little about vibrotactile working memory capacity. While most other domains of working memory are able to store multiple items (for example, the seven-plus-or-minus-two capacity of verbal memory [17]), previous examinations of vibrotactile working memory suggest that stored items may suffer from high levels of interference in the form of overwriting or representation-based interference [2,4], potentially limiting capacity and also limiting our ability to draw comparisons between vibrotactile working memory and other forms of working memory. In the present study, we use a two-item delayed match-to-sample paradigm to demonstrate that subjects are able to store multiple items in vibrotactile working memory, suggesting that interference does not catastrophically limit capacity, and strengthening our ability to compare vibrotactile working memory to other working memory tasks.

1. Introduction

It is generally accepted that working memory is able to store more than one unit of information (for example, the commonly-cited seven plus-or-minus two items [17]). In contrast, there has been relatively little research into the storage capacities of non-verbal forms of working memory, such as vibrotactile working memory. Vibrotactile working memory is an unusual cognitive process, in that it is well understood on the neural level in animal models, and poorly understood in humans. Despite this lack of human research, vibrotactile working memory (VWM) is beginning to grow in popularity as a model system for testing theories of working memory. For example, Bancroft et al. [2,4] recently found evidence for the feature overwriting model of interference with a VWM paradigm. Furthermore, vibrotactile working memory research using human ERP and MEG paradigms [13,29] have provided a substantial challenge to Postle's [21] hypothesis that sensory cortex, not prefrontal cortex, is a critical substrate for working memory storage, as they fail to demonstrate storage of information in sensory cortex during the delay period.

Vibrotactile working memory studies most commonly use the delayed match-to-sample paradigm: subjects are presented with a vibration to the hand (the "target"), followed by a delay period, followed by a second vibration (the "probe"). Subjects are instructed to compare the probe to the target and to decide whether the probe is of a higher or lower frequency than the target, or (in some cases), whether the probe and stimulus are of the same or different frequency. For example, given a target stimulus frequency of 20 Hz, a same-frequency probe would have a frequency of 20 Hz, and a different-frequency probe might have a frequency of 24 Hz. A frequency difference of 4 Hz between the target and a different-frequency probe is common [2,3,6]. These tasks require three separate operations: processing and encoding of target and probe stimuli, maintenance of the target information during the delay period, and comparison of the probe stimulus against the memory store.

Substantial animal research suggests that vibrotactile working memory storage depends on the prefrontal cortex. Researchers examining single-cell recordings in monkeys have identified four areas involved in VWM tasks: primary and secondary somatosensory cortex (SI and SII), premotor cortex, and prefrontal cortex (PFC). PFC, however, is the only area that has definitively been shown to contain stimulus information during the delay period. In humans, Spitzer et al. [29] recently demonstrated that they could compute stimulus frequency based on frontal beta-band activity during the delay period, suggesting that PFC is also the critical area for maintenance in humans.

Of particular interest is the capacity of vibrotactile working memory. It is generally believed that most domains of working memory are able to store multiple items [17,20]. The notion of a rigid capacity limit, however, has been challenged by research into topics such as feature overwriting and chunking. It is well-established that subjects can "chunk" multiple items together and then store those chunks in working memory, increasing their effective memory capacity (even though they may have a finite capacity

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for those chunks) [6,11,16]. Also, Nairne [18] and Oberauer [19] have suggested that capacity limitations may be (at least partially) due to competition between items for a finite set of "feature detectors". Feature overwriting theory suggests that capacity may be a function of item competition for these feature detectors.

While other forms of somatosensory memory have been shown to have storage capacities larger than one stimulus, they are not strictly comparable to vibrotactile working memory. Gallace et al. [10] and Auvray et al. [1] presented subjects with a number of somatosensory stimuli (a maximum of six) to different locations. Subjects were reliably able to report up to three of the stimuli, and up to six using partial-report procedures where subjects were cued to a location and asked to report whether a stimulus had been presented to that location. Notably, however, these studies required the storage of information about the spatial location of stimuli, rather than the properties of the stimuli themselves. As such, it is possible that these numerosity judgments involved verbal coding of information (e.g., "I felt a stimulus on my right index finger and thumb") rather than storage of pure somatosensory information. While increased capacity using partial-report procedures suggests that somatosensory information is stored, it does not preclude a verbal coding component. In comparison, vibrotactile tasks require storage of a scalar property (stimulus frequency), and do not require storage of spatial information. Gallace and Spence [9] suggest that spatial information is encoded using neural systems separate from the prefrontal systems suggested by Romo and Salinas to underlie vibrotactile working memory [22]. Further, as non-human primates have been shown to be effective at vibrotactile tasks, it appears unlikely that vibrotactile working memory relies on verbal coding. As such, vibrotactile working memory would seem to be distinct from other forms of somatosensory working memory. Further, there is evidence that vibrotactile working memory may only be able to store a representation of a single stimulus. Bancroft et al. presented distractor stimuli during the delay period in a delayed match-to-sample task, and found that the distractor interfered with the stored representation of the target stimulus [2,4]. When the distractor frequency was between those of the probe and the target, subjects were more likely to report the probe and target as being the same frequency than when the distractor frequency was further away from the probe than the target frequency. This indicates that the distractor was encoded into memory in some fashion, even though subjects were instructed to ignore the distractor. When subjects made their same/different decision, they were comparing the probe against the contents of memory – a combination of target and distractor, not just the target. This potentially limits VWM capacity.

Alternately, it may be that subjects *are* able to maintain separate representations in memory, despite the tendency for new vibrotactile stimuli to interfere with stored stimuli. Spitzer and Blankenburg have recently produced evidence suggestive of a multi-item storage capacity for vibrotactile working memory [20]. As previously stated, Spitzer et al. developed a method to extract the contents of vibrotactile working memory, based on modulation of beta-band EEG activity [29]. Spitzer and Blankenburg presented subjects with two target stimuli, and cued subjects to maintain only one of those stimuli during the delay period [28]. After cue presentation, subjects displayed EEG activity consistent with storage of only one stimulus. As subjects did not receive the cue until after presentation of both target stimuli, Spitzer and Blankenburg's findings are consistent with a multi-item storage capacity for vibrotactile working memory. However, in their paradigm, subjects did not store both items over the entire delay period, and only held one item in memory upon presentation of the probe stimulus. It is possible that had subjects continued to hold both stimuli in memory, catastrophic interference with one or both stimuli may have occurred during maintenance or decision-making. As such, the question of whether vibrotactile working memory can store multiple items is still unanswered.

The present study aims to clarify whether vibrotactile working memory can store more than one stimulus – a question that is important for the ability to compare vibrotactile working memory to other working memory systems. The present study extends the standard delayed match-to-sample paradigm by presenting subjects with not one, but two target stimuli in each trial. Probe stimuli were either the same frequency as one of the target stimuli, or different from both. In the case where the probe was a different frequency from the target stimuli, it was either separated from both targets by 4 Hz, or separated from one target by 4 Hz and from the other by 12 Hz. If both stimuli are stored in memory, then we would expect performance above chance levels for probes testing memory for both the first and the second target stimuli. Alternately, if only one stimulus is stored in memory, we would expect to see worse performance when a different-frequency probe is 4 Hz away from both target stimuli, than when it is 4 Hz away from one, and 12 Hz away from the other. As pointed out by Romo and Salinas, PFC neurons compare the frequencies of target and probe stimuli by calculating the difference between the probe stimulus and the target stimulus [22]. If this difference exceeds some decision criterion, subjects respond "different", if not, subjects respond "same". If both targets are stored in memory, then we would expect the calculated probe/target difference to be smaller than when the probe is 4 Hz away from both targets than when the probe is 4 Hz away from one target, and 12 Hz away from the other.

2. Methods

2.1. Subjects

Twelve undergraduate students at Wilfrid Laurier University participated for course credit. All subjects self-identified as right-handed.

2.2. Apparatus and procedure

Subjects were presented with vibrational stimuli to the right index finger using a magnetomechanical device similar to those used by Graham et al. [12] and Bancroft et al. [2,4]. The device was constructed by gluing a nylon screw to a speaker cone, and placing the cone within a plastic housing such that the surface of the screw was flush with the top surface of the housing. The device was driven by WAV files delivered to the speaker, using an IBM-compatible PC running SuperLab 2.0 (San Pedro, CA: Cedrus). To mask any residual sound from the device, subjects were presented with white noise through headphones, and volume was adjusted until subjects reported they did not hear any residual sound.

Subjects engaged in a brief (40 trials) delayed match-to-sample practice session before beginning the experiment. Subjects were presented with two 1000 ms stimuli, separated by an unfilled 1500 ms delay period. Target and probe stimuli were either the same frequency, or different frequencies, with frequencies separated by 4 Hz. Subjects were instructed to make a "same" response (by pressing the 's' key) if they believed the probe was the same frequency as the target, and a "different" response (by pressing the 'd' key) if they believed the probe was a different frequency from the target. Subjects were provided with visual feedback on accuracy during the practice session.

The present experiment differs from the standard delayed match-to-sample design by presenting subjects with two consecutive target stimuli. During the actual experiment, subjects were presented with three consecutive 1000 ms stimuli, separated by unfilled 600 ms delay periods: Target 1 (referred to as T1),