NASA/TM—2016–219208

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April 2016

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ACKNOWLEDGEMENTS

This work was supported by NASA's System-wide Safety Assurance Technologies (SSAT) Project. We appreciate the assistance of our colleagues in the Advanced Controls and Displays Laboratory at NASA Ames Human Systems Integration Division

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Table of Contents

List of Figures and Tables

Acronyms and Definitions

ANOVA ....analysis of variance

CFQ............................cognitive failures questionnaire

fMRI ....functional magnetic resonance imaging

HSIRB.........................Human Subjects Institutional Review Board (at NASA Ames Research Center)

HUD...........................head-up display

M ....mean

ms ....millisecond

NASA ....National Aeronautics and Space Administration

NTSB ....National Transportation Safety Board

PDA ....personal digital assistant

SD ....standard deviation

SDK ....software developer kit

A Touchpad-Based Method for Inducing Attentional Tunneling

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Attentional tunneling is a recognized problem for aviation safety in the flight deck. A prototype system (touchpad and associated application and experimental software) was developed and evaluated for its success in inducing attentional tunneling in a reliable and predictable manner in training and experimental contexts. Two experiments involving a total of sixteen participants examined baseline performance for visual memory of a color or number sequence, simultaneous with performing a competing auditory detection task. Spatial auditory separation of the auditory stimuli was also evaluated. Data are provided for various aspects of touchpad entry (accuracy, speed) as well as hit and false alarm rates for the auditory task. The results will help determine means of inducing attentional tunneling in more complex flight simulator experiments, and for developing an inexpensive prototype for pilots to measure cognitive fixation and develop mitigation strategies.

1. Introduction

Attentional tunneling in an aviation context refers to pilot safety issues related to inadequate task management or prioritization (Wickens & Alexander, 2009). It is defined as "...the allocation of attention to a particular channel of information, diagnostic hypothesis, or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks" (Wickens, 2005). The phenomenon has been referred to in the literature more generally as "cognitive fixation" or "cognitive capture" and is related to the phenomenon of "inattentional blindness" for unexpected visual events (e.g., the famous video of the "invisible gorilla" walking in the midst of a basketball game (Simons & Chabris, 1999)). A related cross-modal phenomenon is known as "inattentional deafness" (Macdonald & Lavie, 2011), where a visual stimuli task with high cognitive load is capable of causing failures in detection of auditory stimuli.

The U.S. National Transportation Safety Board (NTSB) states that approximately half of aviation accidents can be attributed to human error caused by inattention of the crew (NTSB, 1994). For example, the Eastern Airlines 401 accident of 1972 was caused by preoccupation of the crew on a landing gear problem, while ignoring auditory warnings regarding descent (NTSB, 1974). Research

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into the underlying causes of pilot error caused by attentional tunneling has generally focused on perceptual load, automation and displays of cockpit information, along with the negative impact a particular display configuration may have on the pilot and their attention. For example, head-up displays (HUDs) can direct visual attention to near-field symbology but simultaneously cause delayed responses to important far-field stimuli (such as other aircraft on the runway that could potentially result in an incursion (Foyle, et al., 1993), due to the inability to monitor multiple streams of information simultaneously (Wickens & Long, 1994).

Subjective awareness in high-stress environments is determined in part by available cognitive "resources" capable of responding to sensory input (e.g. Wickens & Yeh, 1988). If a task such as landing a commercial aircraft or texting while driving exhausts available attentional resources, the possibility of attending to stimuli outside of the task is decreased. The increase in accidents caused by driving while texting on cellular telephones or personal digital assistants (PDAs) has increased attention to the "multitasking myth:" the brain can only rapidly switch attention in a sequential manner and has limited capacity for attention. The brain is constantly engaged in an encoding process of selecting which stimuli to attend to, processing of information, and memorization. In addition, it is engaged in cognitive retrieval of that information, and execution of actions on that information. The encoding process of attention involves different neural pathways and areas of the brain, dependent on the type of stimuli. For example, fMRI data has shown that cell phone usage, involving listening and language comprehension centered in the temporal lobe, can remove activity from the parietal lobe associated with the spatial processing associated with driving (Schweizer, et. al, 2013).

There are multiple examples in cognitive science *of dual task paradigm* studies, where the difficulty of one task influences performance on another task, and performance on the two done together is compared to performance on a single task. The theory is that each task competes for cognitive processing resources and attention (Wickens, 1991). In such studies, the effect of cognitive overload is demonstrated, where human processing resources are shared between the tasks and the effects of the limits of capacity are demonstrated.

A related study paradigm that focuses on reaction time in a dual task situation is the *psychological refractory period*, where the stimulus onsets are asynchronous; varied onset is asynchronous in order to demonstrate the effects of processing of the first stimulus on reaction time to the second stimulus. Other related study paradigms include *change blindness/deafness*, which measures sensitivity to small difference in a complex field, and *repetition blindness/attentional blink*, where under conditions of rapid serial presentation, a second stimulus or target is not detected.

In complex task environments such as the flight deck, mental workload level and demands on working memory have been demonstrated to impact the probability of detecting an unexpected stimulus. In some flight simulator studies, the means for overloading attentional resources involves an off-nominal condition (e.g., an engine failure) in a full-mission simulation. Each crew's response to these off-nominal conditions is complex and differentiated, making inter-participant comparisons difficult due to multitude of possible responses to mitigate a particular problem. Furthermore, the introduction of an off-nominal situation can usually be accomplished only once in an experimental block, impeding the ability to gather repeated measures (Wickens, et al., 2009). Other studies have looked at measures of flying performance while manipulating HUD display symbology by averaging over a performance parameter over time; for example Foyle, et al. (1993) examined root mean square altitude and heading deviations as dependent measures. In Steelman, McCarley, and Wickens

(2013), central and peripheral visual tasks were combined: a primary task involved attention to a central flight display while a secondary task involved responses to eccentric targets of varying salience (visual clutter).

Lavie (1995, 2005) and others have established a "load theory" of conscious perception. In this theory, focused attention and, consequently, the ability to detect distractor stimuli depends in part on perceptual load, e.g. perceptual demands of the task performed. Under low levels of perceptual load, there is "spare capacity" that allows processing of task-irrelevant information. This correlates to a "late processing" model where unattended information is perceived and potentially distracting stimuli in essence "spill over" involuntarily. Under high levels of perceptual load there is less processing available for distractor stimuli; perceptual capacity is exhausted by task processing for the "main" stimulus. This correlates to an "early processing" model where attention is allocated selectively, and certain stimuli are in essence discarded. In summary, irrelevant distractors are more invasive under periods of low perceptual load by a primary stimulus, but less invasive under high perceptual load.

Load theory dissociates the effects of perceptual load from *working memory load*, i.e., the relative amount of working memory allocated to a particular task. When working memory load is increased, distractor stimuli processing is increased and become more noticeable due to "a more active executive control function" compared to the passive nature of perceptual load (Macdonald and Lavie, 2008). An increase in working memory ("cognitive control load") causes slower reaction time due to loading of cognitive control function, attributable either to switching of attention or memorization of unrelated information such as digit streams. Therefore, the impact of distracting or "secondary" stimuli on a primary task depends on the mental processes involved:

> The opposite effects of perceptual load and cognitive control load show that it is important to consider the precise nature of the mental processes that are loaded in a given task. The opposite pattern (more distraction with high cognitive control load but less with high perceptual load) also rules out general task difficulty as an account for the effects of either type of load (Lavie, 2010).

Recently, attention has been given to the phenomenon of inattentional deafness, where an increase on perceptual load in the visual modality has resulted in a failure to notice an auditory stimulus. In Macdonald and Lavie (2011), an unexpected auditory stimulus presented at the conclusion of a series of visual tasks was missed more often when the perceptual load of the visual tasks was comparatively high. Raveh and Lavie (2015) found similar results, even when the auditory stimulus was highly expected. In these studies, the manipulation of perceptual load was effected by the complexity of a visual target search, as opposed to manipulation of working memory load.

The goal of the present experiment was to induce and measure tunneling in a predictable and reliable manner; to include both an acoustic and a visual component; and to explore a method to alleviate the paucity of stimuli per block for calculating dependent variables of hit rate and reaction time. To accomplish these goals, the "unexpected stimuli" experimental paradigm typically used for studying inattentional blindness (or deafness) studies was modified. The usual approach is to task the subject with varying levels of cognitive load and then to include an unexpected type of second stimulus, e.g. once towards the end of a block, to measure detection rates. As a result, there are practical limits on the amount of times a subject can be surprised. Here, a dual-task paradigm between visual sequence memorization and auditory recognition was established that allowed for multiple iterations throughout a block, thereby increasing the data available for analysis. The task concerned call sign and number/color sequences that were quasi-relevant to a flight task and that could be run simultaneously in a more complex flight simulation. Rather than using the element of surprise, we took an approach based in signal detection theory whereby a criteria shift (bias) favoring performance in one task over another would be imposed by the type of feedback provided (Green & Swets, 1966). Hence, measures of failing to detect a "surprising" stimulus, as in most inattentional blindness studies, was replaced by failures to detect a stimulus for which subjective bias could cause inattention.

In this study, a touchpad application was developed to measure human performance (timing and accuracy) in recalling a visual number or color sequence and correctly detecting an auditory number sequence (corresponding to ownship call sign number). These are referred to hereafter as the "auditory detection task" and the "visual memory task." By providing positive feedback only for the visual memory task (in the form of affirming auditory feedback and visual score), we predicted that we could intentionally bias the participant towards performing optimally on that task at the cost of degraded performance for the auditory identification task. Attentional tunneling is therefore defined in this experiment as a significant decrease in the number of auditory task hits; that is, a decrease in the number of correctly identified spoken call sign numbers within the continuous stream of random spoken numbers presented. We assume that performance would be nearly perfect if only the auditory identification task were present, because of the high signal-noise ratio and low cognitive task load. The touchpad for stimuli presentation and data gathering was an Apple iPad II, running the iOS 5 operating system. Custom software was developed using the iOS software developer kit (SDK) from Apple.

2. Method

2.1 Participants

Sixteen total participants (age range 18–40) were recruited from the San Jose State University Research Foundation subject recruitment office at NASA Ames Research Center; ten participants in experiment one and six participants in experiment two. All participants had normal or corrected to normal vision and normal hearing. The experiment was conducted under conditions approved by the NASA Ames Research Center Human Subjects Institutional Review Board (HSIRB). All participants were compensated for their participation.

2.2 Design

Two separate experiments were run with related but differentiated designs. For experiment one, a 2 x 2 (auditory input x sequence modality) within-subjects experimental design was employed. The experiment consisted of four conditions (binaural sound, numerical sequence; monaural sound, numerical sequence; binaural sound, color sequence; or monaural sound, color sequence) with 5 blocks per condition. The block order was randomized between and within subjects. See Table I.

The goal of the experiment was to compare degradation in auditory task performance as a function of binaural versus monaural audio presentation and the type of sequence (numerical or color).

Table I. Experimental Blocks, Experiment One				
Sequence	*Numerical*	*Numerical*	*Color*	*Color*
Audio:	Binaural	Monaural	Binaural	Monaural
	Block 1	Block 1	Block 1	Block 1
	...	...	...	...
	...	...	...	...
	...	...	...	...
	Block 5	Block 5	Block 5	Block 5

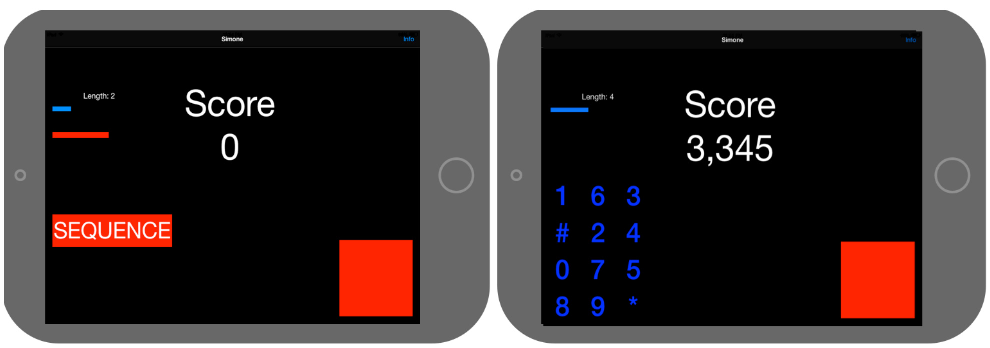

Figure 1. Touch pad screens at start of sequence (left) and randomized keypad for response (right).

The second experiment was run as a control for determining the effect of the auditory stimulus on performance in the sequence memorization task. There were two conditions in a within-subjects design (ref. Table II). The first condition was the same as the "numerical sequence with binaural audio" condition of experiment one. The second condition was the same as the first condition but eliminated the auditory detection task. Five blocks were evaluated for each condition, and the block order was randomized between and within subjects.

Table II. Experimental Blocks, Experiment Two

Sequence	*Numerical*	*Numerical*
Audio:	Binaural	(No call sign)
	Block 1	Block 1
	...	...
	...	...
	...	...
	Block 5	Block 5

2.3 Experimental Task: General

The experiments took place in a soundproof booth; participants were seated at a desk with a touchpad as the source of visual stimuli and for manual response input. Participants wore headphones to listen to auditory stimuli presented at a normal conversational level of approximately 55 decibels. Each block lasted approximately 200 seconds, terminating once 10 presentations of an auditory target were presented and the last memorization task was completed. Participants were instructed to accomplish tasks as quickly and as accurately as possible, and to weigh the importance of the tasks equally. Following the completion of an experimental block, subjects entered the "performance score" indicated on the touchpad onto a sheet of paper with a pencil, so that they could review their score "history."

Prior to starting the experiment, participants were instructed on how to perform the task as well as given two practice trials for each response modality (number sequence, color sequence). A cognitive failures questionnaire (CFQ) was administered (Broadbent et al., 1982) for experiment one to determine if a correlation between self-perceived incidents of inattention and performance on an auditory detection task existed.

The touchpad for stimuli presentation and data gathering was an Apple iPad II, running the iOS 5 operating system. Custom software was developed using the iOS software developer kit (SDK) from Apple.

2.4 Visual Memory Task

In response to visual stimuli, an "*n*-back task" was performed by touching correct response "buttons" on the computer touchscreen. An *n*-back task is an experimental technique used to assess working memory during a continuous performance task (Kirchner, 1958). Here, the overall task was to recall a sequence of numbers or colors presented as visual stimuli, while simultaneously detecting an auditory stimulus. The task was similar to that developed for marketed electronic memory games such as "Simon" that first appeared in the 1970s (Morrison & Baer, 1977).

Details of the *n*-back task were as follows: at intervals randomized between 2 and 4 seconds from the start of the block or after the completion of a prior sequence, a button labeled "sequence" appeared (Figure 1, left) and a "sequence alert" chime was played diotically (a monaural signal delivered to both channels of the headphones). Participants were instructed to press the sequence button as quickly as possible, initiating the presentation of a series of numbers or colored squares for the memorization task. Depending on the block type, a sequence of numbers (0–9) or colors (red, blue, yellow, green) was presented at a rate of one per second. After the sequence was presented, the last number or color sequence disappeared, and a randomized number or color pad appeared in the lower left corner of the touchpad for response input (Figure 1, right, shows an example of the number pad). Participants were instructed to enter the memorized sequence as quickly and accurately as possible, in order to increase their "performance score" which updated in the center of the display throughout the block.

Brief "positive" and "negative" auditory chimes provided immediate feedback following a correct or incorrect sequence entry. The response keypad disappeared and the negative auditory chime was played at any point the sequence was incorrectly entered. The "sequence alert," "positive" and "negative" chimes corresponded respectively to the "telegraph," "complete" and "descent" feedback sounds included as part of the iOS operating system. Auditory feedback for contacting a button on the touchpad was provided from a recording of a button click.

The sequence presentation was based on an adaptive staircase algorithm: it began with two items and increased by one item with two successive correct answers, or decreased by an additional item with one incorrect answer, until the minimum of two items was reached. On average, there were 18 sequences per block, or 360 sequences per subject, of which ~77% were correctly input.

2.5 Auditory Detection Task

In addition to the *n*-back visual memorization task, participants performed an auditory detection task (in all but half of the blocks of experiment two). Through headphones, they monitored a continuous stream of randomized three-digit call signs (e.g., "2-9-2", "8-9-3", etc., duration 2 seconds) spoken in monotone by a male talker. Participants were instructed to tap a square red button that was consistently located in the lower right of the touchpad display (ref. Figure 1) as quickly as possible when they heard the target call sign "3-9-3," which was assigned as their personal "call sign."

In the binaural condition of experiment one, the call signs were played to the left ear only to allow dichotic segregation from the other sounds (sequence alert, positive and negative chimes) that were related to the visual memorization task. In the monaural condition, they were played diotically (the same signal to both ears). We hypothesized that detection of the call sign might be improved with dichotic presentation, since information presented binaurally facilitates auditory stream segregation (Bregman, 1994).

In contrast to the *n*-back memorization task, no visual or auditory feedback was provided for detecting or missing the call sign. Throughout each block, a set of twenty different call signs were called out randomly, with 10% corresponding to a valid target presented throughout a trial run.
In experiment two, the auditory detection task was only performed in five of the ten blocks, and only the binaural playback condition was used. There was no auditory detection task for the other five blocks.

2.6 Acquired Data and Dependent Variables

2.6.1 Performance Score Calculation

The performance scores for the *n*-back task were calculated in two parts using an algorithm that was intended to allow participants to be aware that speed and accuracy were rewarded, but without being aware of the details of the algorithm. Response to the sequence button was calculated by 1000 * (sequence length *n*) where (0 <= *n* <= 1) and *n* = 1 when sequence button appears, with the score reduced by .1 every 200 milliseconds. Length and correctness of sequence entry was calculated by position in sequence multiplied by 25 ms each item is entered correctly. For example, if the sequence button is hit within 200 ms of its appearance and a sequence of 3 items is correctly entered, the calculation is 1000 + (25+50+75) = 1150 points.

The performance score was provided primarily as a biasing element in the experiment, but was analyzed as a dependent variable for analysis in both experiments one and two since it encompassed accuracy and timing in a single value.

2.6.2 Auditory Task Hit Rate, Correct Sequence Entry

In experiment one, we examined the effect of sequence modality (numbers vs. colors) and audio presentation (binaural vs. monaural) on the following dependent variables: hit rate for the auditory task; correct response entry time; and percentage of correctly entered sequences. In experiment two, we analyzed only the percentage of correctly entered sequences, to determine if there was a significant effect on the memorization task due to the presence of the auditory detection task.

2.6.3 Unanalyzed Data

Data was also gathered for each subject on block completion time; response time to the auditory target; mean, minimum and maximum sequence length; and the mean, minimum and maximum duration for entering a correct sequence. For experiment one, we also gathered the false alarm rate for auditory targets. These data were not analyzed for the current report.

3. Results

3.1 Experiment One

A series of within subject analysis of variance (ANOVA) were run to investigate the main effects and interactions that might occur for the independent variables of sequence modality and auditory input on hit rate, sequence score, and percent of correctly entered sequence entries.

3.1.1 Hit Rate for Auditory Target

The means and standard deviations for auditory detection hit rate are presented in Table III. The within-within ANOVA used to investigate hit rate did not reveal a significant main effect for sequence modality, $F(1,9) = .092$, $p = .769$, partial $\eta^2 = .010$, or auditory input, $F(1,9) = 2.007$, $p = .190$, partial $\eta^2 = .182$. A significant interaction also did not occur, $F(1,9) = .397$, $p = .544$, partial $\eta^2 = .042$. These results indicate that neither modality nor auditory input had a measurable impact on hit rate[5]. We note that the mean hit rate of 61.2–65.4% indicates that nearly one out of three instances of the call sign were missed.

Table III. Means and Standard Deviations, Auditory Detection Hit Rate

Condition	*Mean*	*SD*	*N*
Binaural numbers	61.20	23.99	10
Monaural numbers	65.50	23.37	10
Binaural colors	63.80	16.83	10
Monaural colors	65.40	20.44	10

3.1.2 Sequence Score

The means and standard deviations for sequence score for the primary experiments are presented in Table IV. A significant main effect of sequence modality was found, $F(1, 10) = 14.860$, $p = .004$, partial $\eta^2 = .623$. Post hoc analysis with Bonferroni correction identified a decrease in score when the modality presented was numbers (M = 17351.838, SD = 595.065) over colors (M = 18397.540, SD = 658.152), a statistically significant mean decrease of 1045.702, 95% CI [432.047 to 1659.348], $p <.05$.

The main effect of auditory input was not found to be significant, $F(1,9) = .285$, $p = .606$, partial $\eta^2 = .031$. Nor was an interaction found to exist between sequence modality and auditory input for sequence score, $F(1,9) = .000$, $p = .990$, partial $\eta^2 = .000$.

Table IV. Means and Standard Deviations, Performance Scores, Experiment One

Condition	*Mean*	*SD*	*N*
Binaural numbers	17426.700	1978.146	10
Monaural numbers	17276.975	2110.677	10
Binaural colors	18477.660	2102.591	10
Monaural colors	18317.420	2371.542	10

[5] Partial η^2 (Eta squared) is a measure of effect size. Values < .13 are of small effect size; values > .13 < .26 re of medium effect size; and > .26 are of large effect size.

3.1.3 Percentage Correct Sequence Entry Proportion

The means and standard deviations for percentage of correctly entered sequences are presented in Table V. A significant main effect of sequence modality was found to occur, $F(1, 9) = 27.510$, $p = .001$, partial $\eta^2 = .753$ such that a greater percent of sequences were entered correctly when the modality was numbers (M = .807, SD = .014) instead of colors (M = .752, SD = .015).

The main effect of auditory input was not significant, $F(1,9) = 3.082$, $p = .113$, partial $\eta^2 = .255$ and there was no interaction between sequence modality and auditory input for sequence score, $F(1,9) = 3.456$, $p = .096$, partial $\eta^2 = .278$.

Table V. Means and Standard Deviations,
Percentage Correctly Entered Sequences

Condition	*Mean*	*SD*	*N*
Binaural numbers	.7985	.04403	10
Monaural numbers	.8164	.04746	10
Binaural colors	.7516	.04154	10
Monaural colors	.7530	.05415	10

3.1.4 Correlation between Auditory and Visual Task Performance

The relationship between auditory task hit rate and visual memory task performance was analyzed using a Spearman rank correlation test, for each of the four auditory-sequence type conditions. A significant inverse correlation was found in the binaural numbers condition: as participants' hit rate increased, the percent of correct entries decreased, $r_s(10) = -.744$, $p < .05$. However no significant correlations were found to occur among the other conditions (monaural numbers, $r_s(1) = -.353$, $p = .318$; binaural colors, $r_s(10) = -.285$, $p = .425$; or monaural colors, $r_s(10) = -.116$, $p = .751$).

3.1.5 Cognitive Failures Questionnaire

The relationship between auditory task hit rates and the Cognitive Failures Questionnaire (CFQ) scores was analyzed using a Spearman rank correlation test, for each of the four auditory-sequence type conditions. In all cases, the results were not significant (ref. Table VI).

Table VI. Correlation between Hit Rate and CFQ

Condition	*Spearman's Correlation*
Numbers Binaural	$r_S(10) = .40$, $p = .25$
Numbers Monaural	$r_S(10) = .33$, $p = .35$
Colors Binaural	$r_S(10) = .59$, $p = .07$
Colors Monaural	$r_S(10) = -.06$, $p = .89$

3.1.6 Effect of Modality on Sequence Entry Time

The mean time for correctly-entered sequence entries was analyzed for numerical versus color sequences in the visual memorization task, for sequence lengths of 2, 3, and 4 items. Color sequences were entered more quickly, likely due to the less complex entry response keypad (4 items for colors, versus 10 randomized numerical items). A significant difference between color and number sequences for the visual task was found for all sequence lengths analyzed: length 2, $F(3,27) = 43.92$, $p < .01$; length 3, $F(3,27) = 40.43$, $p < .01$; and length 4, $F(3,24) = 22.72$, $p < .01$. No differences were found between monaural and binaural auditory conditions for either modality.

Table VII. Entry Time for Numerical versus Color Sequences (Mean, Standard Deviation)

	Sequence Length					
	2		3		4	
Sequence Type	M	SD	M	SD	M	SD
Numerical	2.93*	.18	3.55*	.28	4.23*	.30
Colors	2.31*	.16	2.90*	.28	3.58*	.33

* = p <.01

3.2 Experiment Two

A paired t-test used to determine if the presence of the auditory task had any impact on either sequence score or on the percentage of correctly entered sequences. No significant differences were found to occur between sequence score $t(4) = -1.254$, $p = .278$ or percent correct $t(4) = 2.652$, $p = .057$, regardless of auditory task presence.

4. Discussion

The current study examined attentional tunneling using a combination of stimuli modalities, a manipulation of working memory, and particularly in the use of an added a biasing parameter for one of two tasks. The auditory stimuli used were not “surprising” as in Macdonald and Lavie (2011) but instead were presented in competition with a simultaneous primary task to which participants were biased through the use of continuous feedback. Through the use of positive and negative auditory feedback and an actively updated performance score, we attempted to manipulate the criteria of the subjects towards performing well on the visual memorization task, to the detriment of performance on the auditory detection task. A shift in criteria is explained as a form of operator bias in terms of the theory of signal detection (Green and Swets, 1966).

In the first experiment we tested whether attentional tunneling could be deterministically induced to cause attentional focus on a visual memorization task to the detriment of a simultaneous auditory detection task. Evidence of attentional tunneling would be manifested as a low hit rate for the auditory task. This clearly occurred, since the hit rate was 63% overall: i.e., about one out of every three call signs were missed. We assume the hit rate would be nearly 100% in a single auditory task paradigm.

However, the results of experiment one does not allow a conclusion as to whether the missed call signs were due solely to the visual memorization task itself, or to what degree a criteria shift caused by the performance score and the immediate "correct-incorrect" auditory feedback contributed. Experiment two was run as a control for the results of experiment one to determine whether an involuntary attentional allocation between two perceptual modalities was a more likely cause for the missed targets, or if it was more likely caused by the aspects of the experiment used to encourage ("bias") performance on the visual task.

If the level of performance on the visual task degraded only by the presence of the auditory task due to a differential reallocation of attentional resources, and not by the experimental bias manipulation, then performance in a visual-task-only paradigm would be expected to be significantly higher compared to a dual task paradigm. Conversely, a lack of a significant effect would have indicated that participants were maintaining their performance level on the visual task independent of presence of the auditory stimuli, including at the cost of auditory detection performance. In fact, the results of experiment two showed no significant difference in the performance of the visual memorization task when the auditory detection task was present or absent. Despite instructions to participants in both experiments that the visual and auditory (when present) tasks were of equal importance, to be performed "as quickly and as accurately as possible," the results suggest that the "inattentional deafness" to the auditory stimuli was caused by the biasing effects of feedback for the visual task.

The results are consistent with Macdonald and Lavie (2008) who state that, compared to the passive characteristic of ignoring irrelevant stimuli under high perceptual load, "the effects of memory load indicate a more active executive control role: working memory actively maintains stimulus processing priorities in a task, so when working memory is loaded with other task-unrelated material during task performance, the processing of low priority, task irrelevant distractors is increased." The current experiments' visual memorization task is a form of working memory load, and in the absence of a biasing factor, one would expect unrelated auditory stimuli to be attended to at a higher detection rate than found here.

Under the conditions evaluated in experiment one, there was no significant difference as a function of binaural versus monaural presentation. When the call signs were presented binaurally to allow for a cognitive streaming advantage by presentation to a separate ear, we expected that detection might have improved. However, any advantage that may have been present was likely overwhelmed by a biasing effect for the visual memorization task. Due to the lack of significance, the binaural versus monaural condition was not evaluated in experiment two.

We also evaluated in experiment one whether the modality of the visual memorization task (colors or numerical sequences) was a significant factor in performance. We found a significant difference for entry speed in the visual memory task for sequence lengths of 2, 3 or 4, with color sequences entered quicker than number sequences. While this may have been because there were fewer colors than numbers in the response choices (4 versus 10), the temporal advantage may also be due to differential cognitive processing for numerical versus color sequences. In the experiment, the memorization of numerical sequences may have competed with cognitive resources for numerical detection in the auditory task, thereby degrading performance compared to memorization of color sequences. However, examining performance overall, including longer sequence lengths of 6 or more items, the results also showed a significant, if small, increase in accuracy of entering numerical sequences compared to color sequences (75% versus 80%). Finally, reflecting both speed of entry and accuracy, there was a small but significant difference in the performance score used for participants' feedback, favoring color sequence entries.

Performance on simultaneous cognitive tasks is impaired more significantly as a result of task type as opposed to overall cognitive demands (Farmer, Berman, & Fletcher, 1986). A "multiple-component" system has been proposed as the most robust explanation for this difference, where discrete, specialized resources are available for processing and storage of different kinds of information in memory (Baddeley and Logie, 1999; Wickens, 1991).

The magnitude of the impairment for the auditory identification task varied widely between participants (see Figure 2). The variation between individual participant's data indicates a differential bias towards maximizing performance on the visual memory task at the cost of the auditory identification task. It may be that those persons who "scored highest" in the memory task did so by shifting their criterion to the detriment of the auditory identification task. However, a correlation analysis did not indicate a relationship between longer average entry time for a given sequence length and greater accuracy on the auditory task.

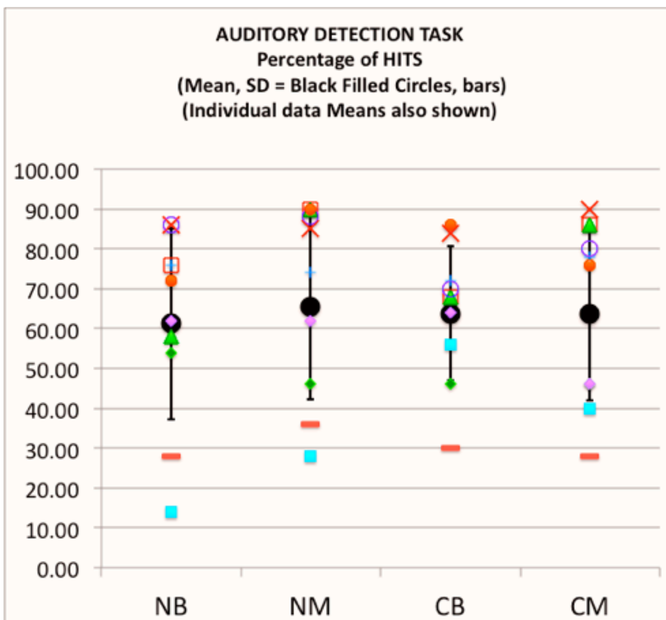

Figure 2. Percentage of hits for the auditory detection task, separated by subjects. Key: NB = number sequence, binaural presentation; NM = number sequence, monaural presentation; CB = color sequence, binaural presentation; CM = color sequence, monaural presentation.

Overall, these findings are consistent with the notion that there are different cognitive mechanisms for recognition versus recall. Recognition of a single item, as in the auditory detection task, has a faster and different level of cognitive processing in comparison to the memorization task where explicit recall of a more complex stored structure was required (Cabeza et al. 1997; Hintzman et al., 1998). Our participants exhibited varying levels of this processing difference, suggesting that levels of aptitude at differentiating tasks may be subject to practice or training.

This study demonstrates that attentional tunneling is a cognitive phenomenon that is possible to induce in a laboratory setting, favoring one modality of information over another. We believe that these results will enable more specific studies of the aspects of task management that lead to pilot error and, in future, enable more effective testing and design of displays and auditory inputs for safe flight. Our research is ongoing in this area, and is focused on near-term applications and longer-term basic research goals. For example, a near-term application of the touchpad-based response paradigm in this experiment has already been proposed as an inexpensive prototype for training pilots about cognitive fixation and for training to develop mitigation strategies.

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