Selective Interference Effects on Working Memory during Navigation

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The extent of memory's involvement with navigation and spatial knowledge is a topic of popular debate in today's media. There is an increased effort to understand how different forms of everyday distractions affect spatial memory from navigation. This field of research is frequently used to address safety concerns involving attention distractions that affect all types of navigators, for instance car drivers, train conductors, or pilots. With the increased availability of handheld distractions such as iPods, cell phones, and texting, there has been an upward trend of news stories emphasizing navigators getting into accidents due to device diversions on memory and attention. This rise in incidents is being countered by various new laws coming into place that attempt to curb distracted driving. However, the creation of laws to effectively combat such accidents is not always clear-cut because it is not fully understood which types of activities may actually cause hazardous distractions and which activities are safe to perform while driving. Some states allow talking on a cell phone while driving, others allow only hands-free cell phone conversations, and still others completely ban cell phone use while driving. The recent Massachusetts law banning texting while driving has only revamped the focus on what are safe navigation practices.

The effects of memory taxing activities, specifically ones that target working memory, have implications beyond navigation performance including involvement with spatial learning and recall functions. More recent research addresses topics of spatial memory impairments due to reliance on technology, such as the increasingly common issue of people getting lost during navigation due to GPS dependency. Recent research by Langston, Ainge and Couey (2010) examines the development of spatial representation systems and alludes to how absolute reliance on GPS for driving directions fosters a growing inability for drivers to complete basic navigation tasks on their own. This apparent failure of spatial representation applies even for simple and repeatedly occurring situations like driving home from work, a task someone might perform daily and should be able to perform automatically. This paradigm is parodied in an episode of the popular NBC television show "the Office," where a main character follows his GPS devices' directions unquestionably driving straight into a lake. While this is an extreme example, it is not far off from the reality that devices and distractions can cause problems with spatial knowledge. Research has also found that cell phones use during navigation can cause performance detriments in driving ability as well as spatial memory (Strayer & Drews, 2007). Such research indicates that cell phone use can have disruptive effects on memory for objects in an environment due to attention division and dual-tasking of memory processes. In both the GPS and cell phone instances, the issue at hand illustrates how accessing multiple streams of memory simultaneously can lead to memory deficits involved with spatial knowledge.

With this knowledge at hand, the present study explores the extent to which spatial memory and recall is influenced by memory distraction tasks as applied to direct navigation experiences. Motivation for this study comes from the apparent deficit of research on the topics of working memory, interference, and recall as they apply to specifically navigational based learning. Furthermore, the results of present study have significant relevance to current topics of scholarly and public concern. These specific topics of research and concern are discussed below.

Working Memory and Learning Environments

According to Baddeley's model, working memory (WM) consists of several components, including the visuospatial sketchpad, phonological loop and central executive functions (Baddeley, 2002). WM is theorized to maintain temporary information and that information is organized or stored in specialized components based on its general characteristics. The phonological loop involves verbal information and manages such information stored in the verbal working memory (VWM) component. For the purposes of the present study, the visuospatial sketchpad involves spatial information and manages such information stored in spatial working memory (SWM). The central executive (CE) component interacts with all types of WM information and offers a form of supervisory control over the various WM components (Baddeley, 1996; Baddeley, Emslie, Kolodny, & Duncan, 1998; Duff, 2000). Previous research has also indicated that the CE functions as a monitor for WM component allocation when multitasking, including performing multiple tasks of the same or even different WM types; the CE is also thought to play a role in selective reasoning and information storage procedures (Brunyé, Taylor, Rapp, & Spiro, 2006; Baddeley & Hitch, 1974; Duff, 2000; Duff & Logie, 2001; Gyselinck, Cornoldi, Dubois, De Beni, & Ehrlich, 2002). Ultimately, these WM components are essential to the present study because there is significant previous research that indicates the three described functions of WM are directly linked with various forms of spatial memory, spatial learning, and general navigation procedures (Brunyé & Taylor, 2008; Brunyé, Mahoney, & Taylor, 2010; De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Meilinger, Knauff, & Bülthoff, 2008; Perrig & Kintsch, 1985; Sholl, 1987; Thorndyke & Hayes-Roth, 1982).

Spatial Memory and Navigation

> *"Finding our way or informing others where to go, or*
> *what an environment is like, requires a complex interplay*
> *of visuospatial, articulatory, and central executive*

processes."

~Brunyé & Taylor, 2008

The capacity to gather information from navigating an environment, store that information, and subsequently call upon that knowledge to solve a spatial task is a process which is not fully understood. A popular theory is that human's form an abstract spatial mental model of an environment which is stored in their memory. This theory dates back to Tolman (1948) who hypothesized that animals develop cognitive maps which they use when faced with situations requiring spatial knowledge to complete spatial tasks. Similarly, Baddeley (2002) conjectured that multiple WM components were involved in the acquisition and use of spatial knowledge, but there was not much research at the time to support that theory. However, there was some previous indication that spatial representations were composed of so called mental models (Zwaan & Radvansky, 1998). Most relevant to sustaining this theory is the more current work done by Brunyé & Taylor (2008) which indicates that that such spatial knowledge is compiled into spatial mental abstractions that involve VWM, SWM and CE processes. This study and other research demonstrates that all three processes are relevant to spatial comprehension, spatial memory, and the development of spatial mental models when dealing with described environments (Ferguson & Hegarty, 1994; McNamara, Hardy, & Hirtle, 1989; Noordzij & Postma, 2005; Taylor & Tversky, 1992). Further research supports the claim that multiple WM components are involved with the development of spatial knowledge, such as the work done by De Beni, Pazzaglia, Gyselinck, & Meneghetti (2005) which demonstrates VSWM and VWM are involved with route and survey perspective memory in processing spatial and nonspatial texts, as well as others that demonstrate SWM and VWM are used to encode environmental information during wayfinding (Garden, Cornoldi & Logie, 2002; Meilinger et al, 2008; Pazzaglia & De Beni, 2001).

There is significant research to support the theory that WM is involved with environmental learning, but it is also important to understand that spatial memories are developed by the flexible interaction of multiple WM components. It is often found that combinations of WM processes are used in harmony to encode and utilize complex environmental knowledge, and such component interactions are quintessential to the development of spatial mental models (Brunyé & Taylor, 2008). Although common sense might adhere to the idea that only SWM is involved with spatial knowledge, research has determined that VWM also has an important role in developing spatial models and applying that spatial knowledge to complex spatial problems. However, the process of spatial learning as well as the application of spatial knowledge has not been fully researched as it pertains to direct navigation experiences. Brunyé and Taylor (2008) offer the example that items of environmental knowledge like landmark names, landmark locations or overall environmental structure each consist of their own set of interacting WM components. The application of VWM in environmental encoding is further demonstrated in research showing that verbal directions are used to form spatial descriptions (Couclelis, 1996; Daniel & Denis, 2004; Denis, 1997; Denis et al., 1999). Meilinger and Knauff (2008) explore this theory at a deeper level and elucidate spatial knowledge as encoded through a combined spatial format and verbal format. An example from their study is the finding that VWM is highly involved with spatial orientation (a SWM task), which is again supported by other research showing there are verbal characteristics to spatial knowledge (Garden et al., 2002). The present study intends to expand upon this knowledge of WM interactions and spatial knowledge as it applies to navigation.

As described in the Meilinger et al. (2008) study, a method to explore this interaction is through selective interference of WM components. Meilinger et al. (2008) accomplished this by creating tasks that place cognitive load on isolated WM components during navigation, making it possible determine which processes are involved with spatial memory. The results of the study indicate that the encoding of spatial knowledge interferes with verbal and spatial secondary tasks. Similarly, Brunyé & Taylor (2008) showed through selective interference of WM that taxing isolated WM components will cause performance decreases due to higher WM load. However, it is not fully understood the extent to which each individual component is involved with encoding environmental information from direct navigation experiences, or which components of WM are subsequently involved in the application of spatial knowledge to problem solving tasks such as route planning and detour avoidance. The present study expands on the results of the Meilinger et al. (2008) and Brunyé & Taylor (2008) studies as it uses an analogous method of selective interference to investigate the novel topic of which specific and isolated WM tasks interfere most with recall performance pertaining to learned spatial knowledge gleaned from navigation. The design of the present study allows for free roam capabilities during navigation, enabling a more realistic setting which should translate into results that are more applicable to real world settings.

Selective Interference of WM components during Navigation

The use of selective interference to test WM is a commonly used procedure and it is understood that our chosen auditory tasks effectively isolate and tax the intended WM components. Selective interference in the present study refers to the method of having a participant respond to a task that suppresses a single and isolated WM component while the same participant simultaneously performs the main task that is intended to be studied, such that any performance differences in the main task can be attributed to that specific WM component; any performance differences would also imply the isolated WM component is involved with learning and memory in the given main task (Brunyé & Taylor, 2008). This method of selective interference to explore the WM task involvement is mirrored in much research, such as Brunyé & Taylor (2008) where secondary interference tasks were used to reveal which WM processes are essential to spatial mental models, as well as the research of the Meilinger et al. (2008) where secondary task interference was used to explore WM involvement with the encoding of environmental information.

Brunyé & Taylor's (2008) work is highly relevant to the present study because the hypothesis being explored utilizes a similar secondary task design to promote WM interference effects. They hypothesize that spatial reasoning involving learning environments (such as map drawing or inference statement verification) requires significant SWM and VWM involvement and thus any performance detriments due to selective interference of secondary tasks would indicate the active use of spatial mental models and/or the use of articulatory mechanisms to represent spatial information. Participants were asked to read and learn two environmental descriptions while completing a secondary task. In the spatial secondary task, participants completed a finger tapping task that placed load on SWM. In the verbal secondary task, participants verbally repeated a designated sequence of syllables that placed load on VWM. After the learning phase, participants completed several recall tasks including a map drawing task, a landmark recall task and a sentence verification task. The results of the study indicate that both the spatial and verbal secondary tasks caused performance decreases in the recall tasks due to interference during the learning phase. This supports the hypothesis that VWM and SWM are involved with the development of spatial mental models. These findings and the design of this study are important to the present study's utilization of the map drawing and landmark recall as memory tasks. The design of the described study is also conducive to our research because it provides support for the use of selective interference as a reliable method of measuring WM involvement in specific spatial knowledge tasks.

The research from Meilinger et al. (2008) is particularly relevant to the present study's method because the secondary task designs are very similar. In their study, participants were shown a video of and asked to learn two routes through a virtual city while performing an assigned WM secondary task (a visual, spatial or verbal task) throughout this learning phase. After the learning phase participants were asked to virtually navigate (using a joystick) the two identical routes they had just learned. They assessed performance using several dependent measures, the most critical being frequency of "getting lost" or straying from the ideal learned path. The specific secondary tasks used in the virtual city study are very similar to the secondary tasks in the present study because they include a spatial task, a verbal task and a control group (no secondary task), but more considerable is that all these tasks use stimuli presented aurally through headphones with responses recorded through a single button press. In the spatial task, participants responded to which direction a sound was originating from in relation to their position. In the visual task, participants were prompted to envision an analog clock with hands and they responded to whether two aurally presented times were on the same half of the clock face. In the verbal task, participants responded to the lexical-decision task where they had to confirm that a given word was an actual word or if it was a nonsense word. The results of the study indicated that wayfinding performance was most inhibited by the verbal and spatial secondary tasks due to selective interference. Participants got lost more frequently when they learned the two routes while completing the verbal and spatial tasks as compared to the control group. This main effect of the findings led to the hypothesis that there exists a process of verbal encoding of spatial information including spatial relations or directions. These findings support the hypothesis that VWM and SWM are involved with the encoding of spatial information during wayfinding.

The Present Study

The present study examines the relationship between individual components of working memory and the processes of both learning environments and successfully applying new spatial knowledge to solve novel spatial problems. The use of virtual environments and secondary task procedures are a powerful way to explore WM as it applies to spatial knowledge in a controlled manner. If selective interference of WM does indeed produce performance decreases in the recall tasks, we predict that navigational based learning and recall performance will be impaired at different rates and by different WM components as produced by task condition. We conjecture that all secondary tasks conditions will cause some form of performance decrease as compared to the control condition due to the basic constraints of memory under more demanding tasks. Based on the design of the study and previous research, we hypothesize that participants in the verbal condition will perform significantly worse on recall tasks compared to the control and tonal tasks because we theorize that verbal working memory is highly involved with spatial knowledge gleaned from navigation. Furthermore, there is a significant verbal element to every recall task that is used to judge participant knowledge, which may cause greater interference effects on learning in the verbal condition. These predictions correlate well with previous research involving WM and spatial reasoning (e.g., Brunyé & Taylor, 2008; Meilinger et al., 2008) but add to the understanding of spatial learning by producing results that can be more generalized to real world navigation.

Pilot Study: Equating WM secondary tasks for task difficulty

Pilot Study: Introduction

We designed our pilot study to test working memory processes and we created three separate WM tasks that require participants to actively use isolated forms of verbal working memory or spatial working memory and a baseline task that taxes general working memory. The collected pilot study data enabled us to modify the three tasks in order to equate them for task difficulty, such that no significant differences existed in hit rates, miss rates, false alarm rates*, or correct rejection rates across task conditions (see Table 1; *false alarm rate not equal for binaural task as compared to all other tasks).

Pilot Study: Method

Participants

A total of 24 Tufts University undergraduate students (15 female, 9 male; age $M = 19.7$, SD = 2.2) participated for monetary compensation. Participants were randomly assigned to one of three auditory groups: tonal, binaural, or verbal task. Participants were recruited through an online student announcement board and the current laboratory participant pool.

Materials

We developed three auditory distractor tasks using binaural, tonal and verbal information. We recorded the binaural sounds using external computer speakers, a digital recording device and in-ear microphones. We fixed a speaker at head height and five feet from the head of an experimenter with in-ear microphones to generate the binaural recordings. The speaker produced a single 500msec tone at a fixed volume. At each of eight 45 degree rotational increments we recorded the tone by having an experimenter wearing the binaural microphones rotate his body in a clockwise direction while maintaining a fixed distance of five feet from the speaker to the center of his head (see Figure 1). In this way, we mapped the binaural recordings onto a pattern that, when presented through headphones, would be perceived as originating from external locations and continually revolving around one's head at 45 degree increments starting from 0 degrees (directly in front of the listener) (see Figure 2). These eight tones were then equalized (for duration and amplitude) as necessary using the freely available Audacity software.

We used the same Audacity software to generate and edit the tonal distractor stimuli, which consist of a series of eight pure tone pitches mapped onto an increasing 21 cent musical interval. Pitch frequency is traditionally measured in Hertz (Hz) but this is a logarithmic measure which complicates creating a series of pitches that increase at a linear rate. As a perceived pitch increases linearly its Hz value increases logarithmically. The solution is to use cents which is a logarithmic unit of pitch intervals where a 100 cent increase corresponds to an increase in perceived pitch of one semitone (the smallest interval in the twelve tone Western music scale). The eight tones we used began at 261.626Hz and increased at 21 cent intervals to form a repeating pattern of eight stimuli, where after the eighth tone the pattern is repeated again from the first tone. We produced the first tone at 261.626Hz because it is the hertz value that represents 0 cents for middle C based on a cents to hertz conversion chart. The pattern included tones of 261.626Hz = 0cents, 264.819 Hz = 21cents, 268.051 Hz = 42cents, 271.165 Hz = 63cents, 274.474 Hz = 84cents, 277.824 Hz = 105, 281.215 Hz, and 284.647 Hz = 126cents.

We created the verbal distractor task stimuli using the freely available voice synthesizer from AT&T Labs Natural Voices Text-to-Speech Demo. The program synthesized eight sound files which included a female voice pronouncing our chosen syllables of "Bah", "Dah", "Fah", "Hah", "Jah", "Lah", "Nah", "Pah". We then edited the syllable sound files using the Audacity software to equate for recording duration and amplitude. We mapped these recorded auditory syllables onto the American-English Alphabet such that when presented through headphones to a listener they form a repeating pattern with a skipped alphabetical position between the first letter of each syllable (B…D…F…H…J…L…N…P…repeat pattern from beginning, B…).

Procedure

Following informed consent, participants sat at a computer monitor running SuperLab. An experimenter asked participants to put on the closed-ear headphones, read the directions presented on the computer monitor, and respond to the sounds presented through the headphones. Participants received either the binaural, tonal or verbal task. The participants received task specific instructions (see Appendix).

The participants' subsequent task incorporated a series of 264 audio stimuli that included the designated repeating pattern interrupted 16 times by randomized pattern changes. These pattern changes included 8 events where 4 stimuli in a pattern were skipped, including 4 skips from stimuli position 3 to stimuli position 7, and 4 skips from stimuli position 7 to stimuli position 3 (Fah…Nah or Nah…Fah; 90º…270º or 270º…90º; 42cents…126cents or 126cents to 42cents) and 8 events where a .5ms silence replaced either the third or seventh stimuli in the pattern. When the participants completed the auditory task they received a debriefing and compensation for their time.

Pilot Study: Results

Results are provided in hit rates, miss rates, false alarm rates, and correct rejection rates based on participant responses to the three given audio tasks. Rates are provided on a 0 to 1 scale based on ratios comparing actual responses versus expected responses to the 264 audio stimuli from each audio task. Means and standard errors for each rate across conditions are used to analyze task difficulty for the three audio tasks. Analysis of the rates indicates that there is no significant difference between rates across conditions, with the exception that the binaural task false alarm rates are significantly higher than in the other task conditions (see Table 1).

Pilot Study: Discussion

The collected pilot study data enabled us to modify the three tasks in order to equate them for task difficulty, such that no significant differences existed in hit rates, miss rates, false alarm rates, or correct rejection rates across task conditions. However, we could not completely equate false alarm rates across all conditions and the false alarm rates for the binaural condition were nearly double the rates for the other two tasks. Although through extensive pilot testing and task modification we did bring the false rates closer, it may be a characteristic of the spatial audio task that participants have a harder time distinguishing actual changes in the stimuli pattern than for the other types of WM taxing stimuli. This might account for our inability to equate false alarm rates for all conditions.

Main Experiment: Working Memory and Learning Environments

We designed our main experiment to test working memory processes as they are involved with memory and recall during navigation by causing selective interference using the three audio tasks from the pilot study. The collected data enabled us to quantitatively compare performance across conditions on both the secondary tasks as well as on the recall tasks. Analysis of the results support our hypotheses as previously described in the present study section of the initial introduction.

Main Experiment: Method

Participants

A total of 64 Tufts University undergraduate students (64 male; age $M = 19.3$, SD = 1.6) participated for monetary compensation. The study drew on exclusively male participants to minimize differences between experimental groups, given gender-based differences in spatial abilities and strategy use (Astur, Ortiz & Sutherland, 1998; Chai & Jacobs, 2010). We randomly assigned participants to one of four auditory groups: tonal, binaural, verbal or control task. We numerically equated the four groups for their scores on the Santa Barbara Sense of Direction Scale, and ran a one-way ANOVA to ensure standardization for video game experience $F(3,60)= .03$, $P>.05$, based on answers to the given questionnaires. To recruit participants, an online student announcement board and the current laboratory participant pool was used.

Materials

The study used two computers, SuperLab 4.0 software, Unreal Tournament 2004 (Unreal Engine 2 by Epic Games, Raleigh, NC), the freely available Input Director software, Sennheiser HD280 closed-ear headphones, and the audio files developed in the pilot study, as described above. A Dell XPS M1530 or Dell XPS Studio 17 laptop attached to a widescreen 17" monitor ran the virtual environments, and an Apple iMac computer with a 21" widescreen monitor ran the SuperLab software. The SuperLab software presented both the questionnaires and the auditory distractor tasks described in the pilot study.

The questionnaires included the video game experience questionnaire (Basak, Boot, Voss & Kramer, 2008), the Spatial Representation Questionnaire (Pazzaglia, Cornoldi, & De Beni, 2000), and the Santa Barbara Sense of Direction Scale (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002).

We created two custom virtual environments using the Unreal Tournament 2004 map editor software (Unreal Engine 2 by Epic Games, Raleigh, NC). These included a practice environment designed to acquaint participants with the Unreal Tournament 2004 (UT) navigation controls (W = forward; S = backward; A = strafe left; D = strafe right; mouse = orientation control; mouse left-click = response for distractor task). This small-scale environment contained non-distinctive buildings and multiple red flags in front of unlabeled landmarks (labels were not present only in the practice task).

The large-scale experimental environment consisted of a realistic urban environment that measured approximately 736,000 square feet and contained multiple landmarks, 16 of which had labels and red flags directly in front to mark them (see Figures 3a-b and 4). The 16 labeled landmarks included: Bank, Campground, City Hall, Construction Site, Courtyard, Graveyard, Hospital, Hotel, Library, Market, Mosque, Police Station, Radio Station, Record Store, University and Theater. Only open space between landmarks (comprising approximately 43% of the environment) was navigable; participants could not enter buildings nor navigate beyond the boundaries of the environment. The characteristics of each labeled landmark accurately reflect the building's commonly known function. During computer based navigation, to walk diagonally across the environment from one corner to the opposite corner with the highest path efficiency it would take approximately one minute. Navigators were given 48 possible spawning locations, with four possible initial starting orientations representing the cardinal directions NSEW. Participants navigated the virtual environment task on the 17 inch monitor at 1440x900 resolution with a simulated field of view (FOV) of 90° from a viewing distance of approximately 2 feet using a standard keyboard and mouse.

A pointing task that tested participant spatial knowledge utilized the same experimental environment, but had the controls for movement removed and participants could only use the mouse to control orientation. The pointing task used an identical spawn system to the navigation task. We designed the pointing task so that participants would be repeatedly spawned in the various locations and asked to point towards labeled landmarks not visible from their starting location. Participants used the mouse to orient themselves so that the flag that marked the specified landmark would be in the crosshairs in the center of the screen. When participants had pointed towards a specified landmark, they would left-click on the mouse, and then would repeat the pointing process. For each pointing trial, participants began at a randomly-determined location (of 48) and orientation (of 4, NSEW), sampling from 192 potential location and orientation combinations without replacement. Participants completed two blocks of 16 trials, during which the target landmarks had random sampling without replacement. If a navigator spawned within sight of the target landmark, the software detected its presence and immediately and automatically spawned him in a different location. The Unreal Tournament software recorded the values for several measures approximately every 50ms, including recorded data for: *Orientation Time:* the time it takes from when the navigator spawns to when they point; *Distance To Target:* the distance from the participant's starting position to the target flag; *Start Offset:* the angle deviation of the participant's view at spawn from the vector between their starting position and the target flag; *Click Offset:* the angle deviation of the participant's view at click from the vector between their starting position and the target flag; *Mean Heading Error:* this measure averages the angle offset at each of the data points of the trial; *Participant Start #:* the starting location (of 48) the trial; *Landmark #:* the target landmark number (1-16); *# of visible landmarks:* total landmarks visible from the trial's starting location.

Procedure

Following informed consent, participants completed the series of questionnaires, administered via SuperLab. Participants then completed a practice navigation task. Before beginning practice navigation, the experimenter explained that the practice task is similar to the actual experimental task. Participants also received the instructions that they would navigate in a virtual environment, where red flags would be positioned throughout the environment and that these flags mark landmark structures. These instructions included that whenever participants' encounter one of these flags they must walk up to and touch the flag by walking directly through it. The experimenter also informed the participant that when they touch a flag in the practice task a verbal prompt appears on the monitor stating that "you have reached a landmark," and then they should continue navigating. The experimenter then explained the navigation controls for navigating the environment and then instructed the participant to explore the environment for 1 minute in order to get accustomed to the controls, while also touching any of the red flags they encounter during navigation of the virtual environment.

After the practice navigation participants put on closed-ear headphones and completed the audio task practice using the mouse-left-click button to respond. The practice audio tasks used the same stimuli and task specific instructions as in the pilot study. Participants received task specific instructions followed by examples of pattern changes and prolonged silences and then completed a practice response series that included the designated repeating pattern interrupted at various points by two pattern changes and two prolonged silences.

Upon completion of the audio practice task, the participants began the main experiment task of navigating a virtual environment while simultaneously completing a full length version of their designated audio task. The experimenter explained to participants that they would be navigating a virtual environment very similar to the practice environment, but this time the red flags around the environment marked actual landmark buildings with specific landmark names. Participants received instructions to navigate the environment and touch the red flags whenever they encountered them and that the experimenter would stop them after 9 minutes. The experimenter told the participant that their primary goal entailed learning the environment to the best of their ability because, immediately after completing navigation, their memory of the environment would be assessed. Participants also received instruction that during the navigation task they must also simultaneously complete the audio task they had just practiced and that the audio task would last for the duration of the navigation task. They could respond to the audio task using the mouse left-click button on the same mouse used to control heading during navigation. After giving participants the complete instructions, the experimenter initiated software on both computers so that the left-click responses on the UT computer mouse would control and be recorded by the SuperLab software on the non-UT computer, via the Input Director Software. At this point participants put on the closed-ear headphones and the experimenter started both the audio task and the navigation task simultaneously, instructing the participants to begin.

Upon reaching the end of the full nine minutes of the combined navigation and audio tasks, the experimenter stopped participants from navigating and exited the UT program. Participants then removed their headphones and moved to the adjacent workstation to complete a series of three recall tasks. The testing phase always began with landmark recall, followed by the pointing task and map drawing, which were presented in a counterbalanced order across participants.

For landmark recall, participants received a blank sheet of paper with a pen and had up to 5 minutes to list all the landmark names they could remember. Upon exceeding the time limit or when the participants informed the experimenter that they were finished, the experimenter removed the sheet of paper containing the landmark names list. Next, participants completed either the map drawing task or pointing task.

For the map drawing task, participants again received a blank sheet of white paper and had up to 5 minutes to draw a map of the environment they had just navigated, labeling landmarks and arranging them in relation to each other. Upon exceeding the time limit or when participants informed the experimenter they were finished, the experimenter removed the sheet of paper with the map drawing.

For the pointing task, participants received instructions based on the description in the materials section above. The experimenter asked participants perform the pointing task until a textual prompt told them the task was complete. Participants then received a debriefing form and compensation for their time.

Main Experiment: Results

Navigation Performance

Two automated navigation performance measures were collected during the nine minutes of navigation, including the number of landmarks visited by the navigator and the total path length that the navigator traveled during navigation.

Landmarks Visited. The results for the navigation performance included the number of landmarks visited by the navigator, which is assessed by the number of red flags that the navigator touched. We ran six independent t-tests and found no significant difference in the number of landmarks visited between secondary task conditions, indicating that participants on average had visited the same number of landmarks regardless of secondary task condition assignment (see figure 5).

Path Length. Navigation performance was also assessed by the path length, or the total distance traveled (in Unreal units) by the navigator. (For purposes of real world comparison, 16 Unreal Units = approximately 1 foot or .3048 meters). To analyze path length results between conditions we ran six independent t-tests and found a significant effect only for the verbal vs. control secondary tasks conditions, $t(30) = 2.71$, $p < .05$ (see figure 6). This indicated navigators in the verbal condition traveled significantly farther than navigators under the control condition.

Secondary Task Performance

Four automated secondary task performance measures were collected for each secondary task condition, which includes response data for hit rates, miss rates, false alarm rates and correct rejection rates. Using a one-way ANOVA we assessed that the results for miss, false alarm and correct rejection rates did not differ. Also, hit rates were generally low across all task conditions ($M=.41$, $SE=.02$). However, a one-way ANOVA showed a significant effect across secondary task conditions for hit rates, $F(2,47) = 4.48$, $p < .05$. Further analysis using independent t-tests showed only significant effects in hit rates for the tonal vs. verbal conditions, $t(30) = 2.68$, $p <.05$ (see figure 7).

Recall Task Performance

To assess participant knowledge of the environment from the navigation task, we administered three recall tasks immediately after navigation, including a landmark recall task, a pointing task, and a map drawing task.

Landmark Recall. Results for the landmark recall task are scored on a scale from zero to sixteen, based on how many correct landmark names of the existing sixteen the participant correctly recalled. The results for landmark recall showed no significant differences, indicating that participants on average recalled the same number of landmark names regardless of secondary task condition, including the control condition. Also noteworthy, recall rates for the tonal and verbal conditions are lower, but only numerically. However, between the binaural and verbal conditions there is a significant difference, $t(30)= 2.95$, $p < .01$ (see figure 8).

Map Drawing. The results for the map drawing recall task are manually assessed by an experimenter by comparing the observed participant generated map to the actual map of the environment. Scores are determined based on if a single unique landmark is correctly labeled in spatial relation to another unique landmark according to actual cardinal direction. Prior to map draw scoring, we generated a list of all possible permutation pairs (120 pairs) of two unique landmarks. From that list, we randomly chose 50 landmark pairs to assess if the participant drawing of the landmark pairs correctly matched the actual landmark pairs in spatial relation, based on NSEW coordinates. For each actual landmark pair we determined which direction one landmark was in spatial relation to the other, and then chose the direction that was the greatest and thus most recognizable distance away. For example, if you traveled the optimal path from the University to the Courtyard, you travel south and east, but a further distance south than east; thus we used the southern direction when scoring the map draw, so if a participant labeled the Courtyard south of the University by any distance it would be marked as correct. We used this procedure to determine the correct cardinal relation for each of the 50 landmark pairs.

Prior to scoring each individual participant generated map, an experimenter compared the observed drawing to the actual map and attempted to orient the observed map such that its orientation corresponded to the actual map based on the relation of the labeled landmarks. This pre-orientation of the drawn map is necessary to properly score the map drawing because during navigation participants were initially spawned randomly facing either of the NSEW directions but were never informed of such direction. Thus, the layouts of the participant generated maps are subject to their individually perceived cardinal position, such that the cardinal orientation of the participant generated map may not correspond to the actual map. Once the participant generated map was rotated to match the actual map, an experimenter analyzed each of the 50 chosen landmark pairs and scored the map on a scale from 0 to 50 based on the scoring system where if the chosen landmark pair was drawn in the previously determined correct cardinal/spatial relation, then participant would receive a single point. The participants' scores were then converted into a proportion before being analyzed. To analyze map drawing results we ran a one-way ANOVA and found a general effect across tasks conditions, $F(3,63) = 3.02$, $p < .05$. To analyze the data between the conditions, we ran six independent t-tests across conditions and found a significant effect for the control vs. verbal conditions, $t(30) = 2.37$, $p < .05$, and a significant effect for the binaural vs. verbal conditions $t(30) = 2.99$, $p < .01$. This indicates participants in the verbal condition performed significantly worse on the map drawing task than in the control and binaural conditions (see figures 9a-b).

Pointing. Participant performance on the pointing task was assessed by their click offset, or the angle deviation of the participant's view at click from the vector between their starting position and the target flag. The angle of the click offset was measured in degrees. The results for click offset were not significant across all task conditions, indicating there is no effect of the secondary tasks on click offset. Participant orientation time was also recorded, which measures the amount of time (in msec) from the start of each pointing trial until the participant left clicked to confirm a point. The results for orientation time were significant for the verbal vs. control, verbal vs. binaural, tonal vs. control, and tonal vs. binaural conditions, indicating participants in the verbal and tonal conditions took significantly less time to complete a pointing trial (see figures 10a-b).

Main Experiment: Discussion

The present study investigated the effects of working memory interference on memory and recall for information learned during navigation of a virtual environment. Data from the present study converged to support our hypothesis that verbal working memory is significantly involved with spatial memory gleaned from navigation. This hypothesis is substantiated by the results from the secondary and recall tasks, particularly the map drawing scores, the secondary task hit rates, and the participants' path lengths during navigation. The present data also implicate that all conditions of WM secondary tasks caused impairments with recall performance, but the VWM condition navigators experienced greater deficits in recall scores as compared to the tonal task or the control condition. The most important measures come from comparing WM conditions to the tonal condition. We consider the tonal task to be a baseline task for comparison purposes because it taxes WM in general but not specifically verbal or spatial WM components. This baseline tonal condition gives a central reading on expected performance decreases during the combined navigation and audio task. The verbal task is very similar in design but different in WM component recruitment, because it uses a similar repeating pattern of 8 audio stimuli, but the use of spoken syllables for stimuli makes this task more verbal in nature. This concept applies to the spatial task as well, where the use of binaural recording makes this task recruit more specifically spatial information. The tasks themselves are very similar and were standardized for task difficulty which allows them to be quantitatively compared. Thus, any positive or negative performance differences in a given condition as compared to the tonal condition highlights the involvement of a certain WM component in a specific type of spatial knowledge.

Navigation Performance

In order to certify that performance decreases in recall tasks were due to secondary task interference and not random effects due to unexpected differences between conditions on navigation itself, we created the *landmarks visited* automated measure. The results show that participants on average visited the same number of landmarks regardless of condition, which validates the described performance decreases assumption above. The other significant measure of navigation performance is *path length.* Participants in the verbal condition traveled significantly farther as compared to the control condition, and numerically farther than any other condition. This implies that navigators in the verbal condition had less familiarity with the environment and that they needed to re-visit map locations more frequently to learn them sufficiently. Furthermore, this extended path length measure for the verbal condition implies more constant movement during the navigation phase, with less time spent stopping, looking around, and learning the finer details of the surroundings. A possible explanation for this is that participants in the verbal condition may have had more difficulty dual-tasking between the navigation and distractor tasks, thus they may focus attention primarily on the audio task and unconsciously continue to hold the navigation buttons. Anything seen in the environment during this unconscious navigational period may not be encoded in memory at all. This theory is supported by the fact that verbal task hit rates were the lowest for any condition, which supposes interference in the opposite direction where participants focusing mainly on the navigation task had a more difficult time attending to the verbal audio task than in any other task condition. If this is the case, then it represents a similar situation to the GPS dependency previously described. In both instances navigators see the environment in front of them, but do not register the spatial information, which manifests as performance decreases in any subsequent spatial knowledge tests.

Secondary Task Performance

In order to ensure that participants were actually attending to the secondary tasks and not just paying attention to the navigation task, we analyzed the secondary task data for any discrepancies in performance between conditions. Results for miss, false alarm and correct rejection rates were not significant, which follows suit with the pilot results that show standardization of task difficulty. More to the point, observed hit rates were generally low for all tasks, but without apparent floor effects. This certifies that participants actually attended to both tasks as expected, and it shows that dual-tasking between navigation and the secondary tasks caused some degree of performance inhibition regardless of condition. However, the verbal task condition had the lowest hit rate of all conditions, and was significantly less than the tonal task condition. This difference is important because it indicates that the verbal qualities of the task caused more interference than found in the baseline tonal task, thus VWM can be understood to have strong implications in spatial memory. Once again, such negative effects are possibly due to increased difficulty for participants to dual-task between navigation and a verbal task compared to other working memory taxing tasks.

Recall Task Performance

The initial task given to participants in the recall phase was always *landmark recall* because this information needed to be recorded so that it could not be supplemented by new information gleaned in the pointing task where participants could again see the same environment. Results show that participants on average remembered the same number of landmarks regardless of condition, and they remembered almost all landmarks in each instance.

This measure may be subject to ceiling effects, but is a good indication that participants saw most landmarks in each condition, which further certifies that any performance decreases in recall tasks can be mainly attributed to selective interference of WM. The second recall task given was counterbalanced between map drawing and pointing.

Results in the *map drawing* task indicate participants in the verbal condition performed significantly worse compared to the control and tonal conditions. Participants' ability to correctly show spatial relation between observed landmarks was significantly worse due to verbal interference from the secondary task. This is a powerful measure because it is significant in comparison to both the baseline and the control conditions, suggesting that selective interference of VWM impaired navigational based learning more than in any other WM condition. This measure provides the best support for our hypotheses that VWM is highly involved with spatial memory and that the design of our study would reveal strong VWM effects.

The results from the *pointing* task, while not significant, do have intriguing implications. Participants in the verbal condition had the fastest orientation time, but also the greatest numerical click offset (we believe that this effect may become significant using a within-subjects design, as discussed later). This is counterintuitive because one would assume participants who were most familiar with the environment would take the least amount of time to point to a given landmark and should be the most accurate when doing so. Yet, this is not the case as participants in the verbal condition seemed to quickly decide where the designated landmark was but were very far off comparatively. This may be an indication of less familiarity with the environment leading to broader, less accurate pointing (i.e., "the landmark is in this general direction"). The apparent speed of orientation for the verbal condition in comparison to the other conditions may be explained by the fact that participants in the other conditions had more definite knowledge of the environment. Therefore, they may have spent more time attempting to accurately point using more detailed environmental cues they gathered during navigation. The various measures indicating verbal interference had the greatest negative effect on spatial knowledge would support this claim because participants in the verbal condition might have a harder time picking up on such helpful detail cues.

Main Effect of VWM

Upon analysis of all performance factors, the common trend appears that the verbal condition had the worst overall performance rating. The participants in the verbal task had the lowest secondary task hit rate, the lowest map drawing score, and the longest path length. This largely indicates that participants were less familiar and less confident with the information they learned while navigating the environment. The results from the present study support the general literature suggesting that multiple WM components are involved with spatial memory, such as the findings in Brunyé & Taylor (2008) or Meilinger et al. (2008). The results support our hypotheses that VWM is highly involved with spatial learning during navigation and that dual-tasking between navigation and a task placing load on VWM causes the greatest interference effects and significantly impairs spatial recall. These findings are novel in regards to navigation because they support involvement of WM components learning and recall, and because they suggest VWM plays a more significant role in spatial memory than previously understood.

Implications

The present study adds to the growing knowledge of the cognitive process of environmental learning. The results indicate that verbal working memory tasks can cause significant interference with navigation, and dual-tasking navigation with a VWM task greatly impairs performance in both tasks. This provides support for various new laws coming into place that attempt to curb distracted driving, such as bans on cell phones, texting etc. Our results have critical applications to such arguments because they add a new dimension to navigational based performance deficits. Almost all literature involving memory interference and navigation suggest that activities such as texting while driving are dangerous because they interfere with the physical act of driving a vehicle. For example, people will drive with only one hand on the wheel or will constantly remove their gaze from the road to their handheld device. The present study takes a novel approach to this case, implying that tasks which interfere with WM are fundamentally dangerous to complete during navigation because they impair navigators' ability to learn or remember details about an environment. The results implicate that even supposedly helpful technological devices like GPS systems may actually cause hazardous interference due to the use of verbal cues. Design of any devices that may be used during navigation should take this finding into account and can be adapted to reduce verbal memory based distraction. The inferences of the present study provide a deeper and more thorough investigation of the involvement of WM in direct navigation based learning. The overall design of the present study is more realistic than previous research on navigation, primarily because it allows for free, participant based navigation that is un-guided by the experimenters. Unlike previously established route learning the use of the UT environments allows for free roaming and a greater learning flexibility involving the environment. The participants are free to move about as they please, which makes the experience more realistic and closer to what one would experience during actual navigation. Thus, as an overall study of spatial learning from navigation, such a design increases our ability to generalize the results of the study to real world situations.

Limitations and Future Directions

Limitations exist in the design and analysis of the study that may constrain the results and the ability to generalize such results for real world applications. The present study used a between-subject design, and while this may not be a fundamental flaw, there may be significant noise and subject differences effects between the conditions especially in regards to spatial ability. Although we did attempt to equate this measure across conditions using the several described questionnaires, there is no sure measure for defining spatial ability. Future research could repeat the present study with a within-subjects design where participants complete four consecutive days of trials and complete all four combined navigation-distraction tasks.

Another limitation in the original design of the study is that although the distractor tasks taxed isolated WM components, the recall tasks all had some form of verbal element to them. While we hypothesized that this feature of the design would result in higher verbal deficits, the design was kept because there is significant verbal information used in everyday navigation and spatial recall based tasks. Even so, perhaps the main effect of the verbal condition only manifests in the presence of landmark names and not solely spatial information. Future research could eliminate verbal cues in recall tasks by removing landmark names. For instance, instead of verbal landmark cues, images of physical landmarks could be used for participants to indicate pointing task location or arrangement of landmarks for map drawing. In this way the effects might be more accurately teased out in regards to recall performance for truly isolated WM components.

Conclusions

The present study provides solid evidence that tasks which interfere with working memory, specifically those taxing VWM, cause significant impairments with learning during navigation. These negative effects are prevalent in multiple performance areas, evidence that WM distraction can have serious implications in regards to spatial knowledge. The results are specifically applicable to navigation based safety concerns, and provide reasons that GPS dependency may be a more significant issue than it may appear to be. The findings can be used to help determine what types of activities are not compatible with navigational based activities based on how they affect spatial memory. Future research is needed to determine more absolute effects of different WM components on navigational based learning, and such research would be helpful to determine novel spatial problem solutions like detour avoidance and route planning as they apply to more realistic navigation settings.Table 1. *Mean and standard error scores from the pilot study for various automated measures for participant responses to audio tasks for each of the three WM conditions.*

Appendix

Binaural task instructions: "You are about to be presented with some sounds through your headphones. These sounds will seem to originate from various points in space and will travel in a revolving pattern around your body. Press the spacebar anytime you hear any changes to the revolving pattern of sounds; including switches that are out of sequence, or prolonged silences."

Verbal task instructions: "You are about to be presented with some spoken syllables through your headphones. These syllables will be presented in an alphabetical sequence with skipped letters, (Bah, Dah, Fah, Hah, Jah, Lah, Nah, Pah). Press the spacebar anytime you hear any changes to the sequence of syllables; including syllables that are out of sequence, or prolonged silences."

Tonal task instructions: "You are about to be presented with some tones through your headphones. These tones will be presented in the order of a repeated ascending pattern. Press the spacebar anytime you hear any changes to the ascending pattern of tones; including tones that are out of sequence, or prolonged silences."

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Figure Captions

Figure 1. A depiction of how we recorded the binaural tones.

Figure 2. The binaural distractor task; listeners perceive the binaural tones to originate from external locations, starting at 0^{o} and revolving clockwise around their head at 45^{o} angles.

Figures 3a-b. Screenshots from main virtual environment exemplifying navigator perspective, environment characteristics, landmark label design, and red flag presence.

Figure 4. Survey perspective of main virtual environment including the 16 labeled landmarks.

Figure 5. Mean (and standard error) of the number of landmarks visited by the navigators

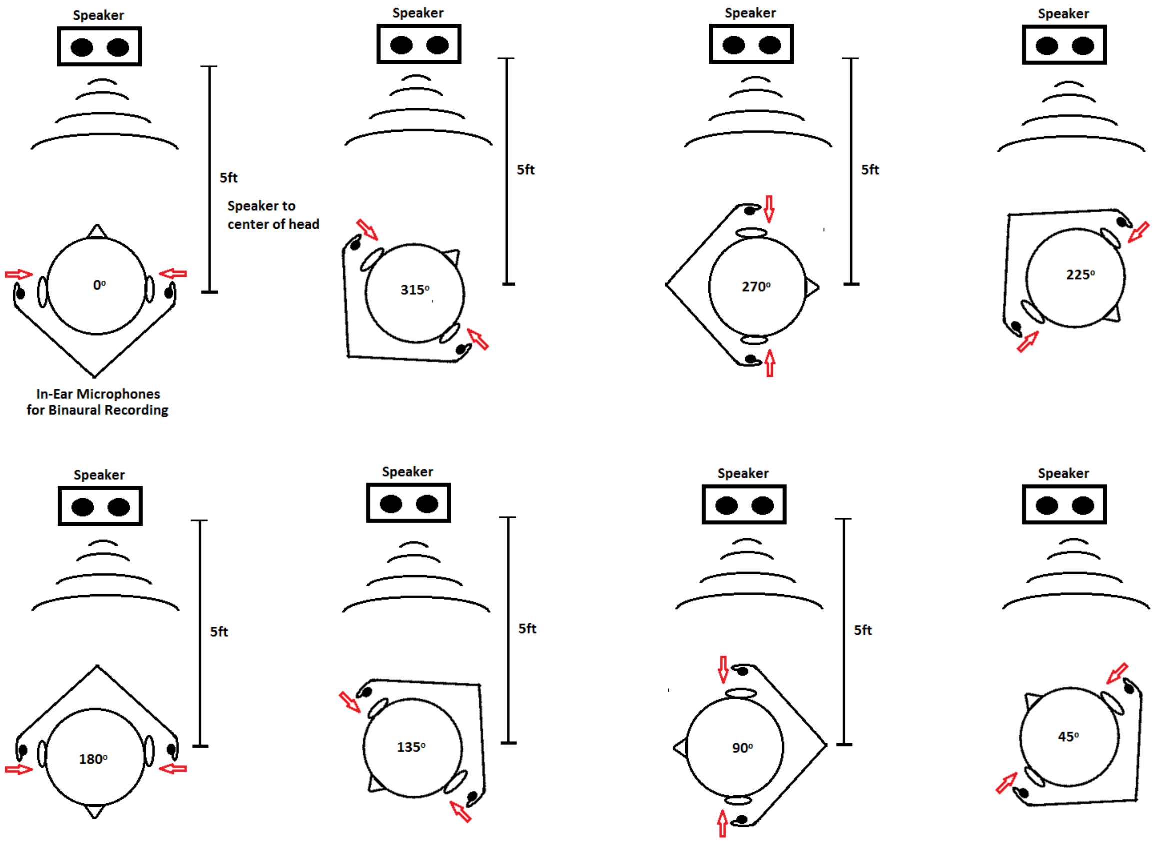
Figure 6. Mean (and standard error) of path length for navigators in all conditions

Figure 7. Mean (and standard error) of secondary task hit rates during navigation

Figure 8. Mean (and standard error) of landmark recall scores for participants in all conditions

Figures 9a-b. Mean (and standard error) of map drawing scores, including score ratios and difference scores as compared to the control condition

Figues 10a-b. Mean (and standard error) of pointing task scores, including the click offset (angle deviation) and orientation times for participants in all conditions


Speaker
5ft
Speaker to center of head
0º
In-Ear Microphones for Binaural Recording
Speaker
5ft
315º
Speaker
5ft
270º
Speaker
5ft
225º
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180º
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Figure 1

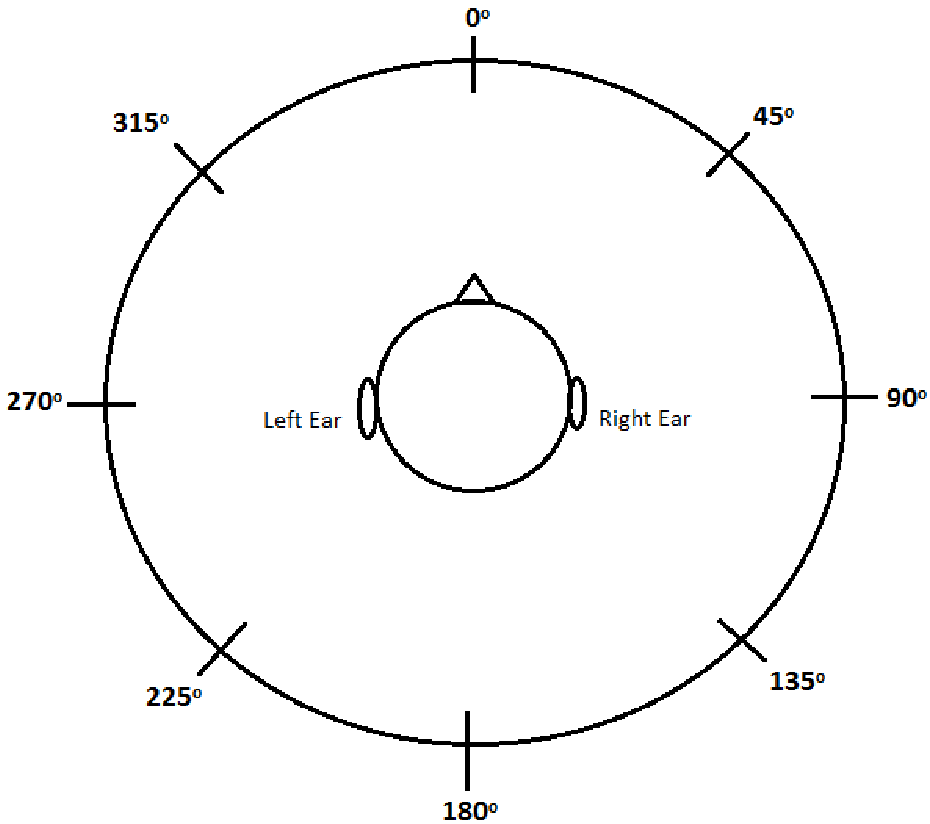
0°
45°
90°
135°
180°
225°
270°
315°
Left Ear
Right Ear

Figure 2


Market
Market
Hotel

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figures 9a-b

Figures 10a-b