Efficient Navigation, Deficient Representation: Exploring How Navigational Aids Impair Spatial Memory

A thesis submitted by

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Abstract

Two experiments examined possible processes by which navigational aids impair spatial memory. Experiment 1 investigated how spatial perspective and information format contribute to spatial memory impairment. Participants navigated with mixed perspective aids (verbal and tonal) or without aid. Both aids yielded slight navigational advantages and steep spatial memory costs. The equivalent impairment between information formats suggests navigational aids impair spatial memory by dividing attention rather than selective interference of verbal working memory. Experiment 2 investigated the extent to which divided attention underlies spatial memory impairment. Presence of navigational aid in a divided attention context did not increase spatial memory impairment suggesting that navigational aids impair spatial memory primarily by dividing attention. Taken together, these findings demonstrate that navigational aids impair spatial memory and suggest divided attention underlies this effect. We advocate future research aimed at minimizing memory costs through design modifications in order to create cognitively ergonomic navigational aids.

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General Introduction

The past decade has seen increased navigational aid use across widely varied contexts. Once solely a military technology, GPS devices and other navigational aids increasingly appear in consumer vehicles, shipping fleets, and mobile phones (James, 2009). A recent market research report (RNCOS, 2011) states that the ready adoption of GPS in fields as diverse as aviation, transportation, and emergency response, has created wide opportunity for market expansion. As such, the report projects that GPS shipments will increase by more than 20% between 2011 and 2013, reaching nearly 900 million units by 2013. Despite this proliferation, the ubiquity of navigational aids has not been met with thorough research on their cognitive impact. Presently, navigational aid research tends to focus on usability, including issues such as cognitive load, divided attention, and interface design (Burnett, 2000; Dewar, 1988; Forbes & Burnett, 2007; French, 1997; Green, 1992; Srinivasan, 1999). While usability remains important, research must also consider, in addition to interaction with the technology, the technology's influence on cognitive processes, with an emphasis on spatial learning and memory (Montello, 2009). The present thesis addresses this need by examining the influence of navigational aids on both virtual navigation performance and spatial memory.

Previous Research

Researchers have only recently examined the cognitive impact of navigational aids. Aporta and Higgs's (2005) ethnographic research on how navigational aids influence the Inuit people provides a good starting point. They described how technological advances, namely portable navigational aids, have affected Inuit hunters' wayfinding behaviors in the Igloolik region. From a young age, Inuit hunters learn wayfinding methods based on environmental cues such as snowdrift patterns, animal behavior, and tidal cycles. Recently, young Inuit hunters have begun relying on portable navigational aids with increasing frequency. The authors argued that these technological and cultural changes reduced the hunters' engagement with their environment, leading to passive navigation. This study, suggesting cultural implications of navigational aid use, serves as an important provocation for future research.

Of the studies examining cognitive processes, the existing research agrees that guided navigation impairs spatial memory, but does not agree on how. Burnett and Lee (2005) make several suggestions based on virtual driving performance. In their study, participants studied a map of a recommended route and then drove the route in a virtual town. While driving, participants either received turn-by-turn verbal directions or navigated without additional aid (control). Aided participants performed poorly on post-navigation spatial memory assessments relative to the control group. Possible explanations offered implicate decision-making processes, attention, map study time, and navigation stress.

Other research has supported specific explanations offered by Burnett and Lee (2005). In line with Aporta and Higgs (2005), other ethnographic research has cited decreased environment engagement as the main contributor to spatial memory impairments during guided navigation (Girardin & Blat, 2010; Leshed, Velden, Rieger, Kot, & Sengers, 2008). Cognitive research, on the other hand, has implicated lack of active investment in terms of mental effort and control (Parush, Ahuvia, & Erev, 2007; Péruch & Wilson, 2004), lack of spatial decision making (Bakdash, Linkenauger, & Proffitt, 2008; Bakdash, 2010), technological novelty (Ishikawa, Fujiwara, Imai, & Okabe, 2008), and divided attention (Fenech, Drews, & Bakdash, 2010). Clearly the debate has not been resolved, but whether this is because the contributing factors interact or because of wide methodological variation is unclear. Further, existing work has not considered some important spatial cognitive concepts. Experiment 1 addresses some of these considerations while Experiment 2 builds on Experiment 1's findings to better elucidate the cognitive processes by which navigational aids impair spatial memory and influence spatial mental representation.

Theoretical Background - Experiment 1

Spatial Perspectives

One important spatial cognitive concept to consider is *spatial perspective*. When learning a novel environment one can learn and form a mental representation from different spatial perspectives (Levelt, 1982; Linde & Labov, 1975; Siegel & White, 1975; Taylor & Tversky, 1992; Thorndyke & Hayes-Roth, 1982; Tversky, 1991; Tversky, 1996). *Route perspective* is characterized by a ground-level, first-person representation, similar to a path within the environment. In contrast, *survey perspective* is a map-like, configural representation from a bird's eye view. Several factors influence how spatial perspective is integrated into the mental representation, including individual preferences (Pazzaglia & De Beni, 2001), learning medium (Taylor, Naylor, & Chechile, 1999; Thorndyke &

Hayes-Roth, 1982), and learning goals (Brunyé & Taylor, 2009; Taylor et al., 1999). For example, studying a map tends to reinforce a survey mental representation, but studying a map with the goal of learning routes facilitates information retrieval from a route perspective (Taylor et al., 1999).

Regarding navigation, Siegel and White's (1975) seminal work on spatial knowledge development posits a model whereby navigators gain new environment knowledge in sequential stages. According to this model, navigators first gain landmark, then route, and finally survey information. More recent research has suggested that landmark, route, and survey information build in parallel (Ishikawa & Montello, 2006). Whether spatial knowledge types develop in serial or parallel, it is generally accepted that navigation experience in novel environments leads more readily to route knowledge (also see: Ruddle, Payne, & Jones, 1997; Shelton & McNamara, 2004; Thorndyke & Hayes-Roth, 1982). This is important to consider given that spatial perspective during learning influences and shapes the mental representation of that environment (Brunyé & Taylor, 2008; Brunyé, Rapp, & Taylor, 2008; Brunyé & Taylor, 2009; Evans & Pezdek, 1980; Lee & Tversky, 2005; Perrig & Kintsch, 1985; Richardson, Montello, & Hegarty, 1999; Schneider & Taylor, 1999; Shelton & McNamara, 2004; Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982). As such, early navigation learning may promote route-based mental representations.

Navigational aids, in the information they provide, may reinforce a particular spatial perspective. Typically, navigational aids provide sequential turn-by-turn directions, reinforcing a route perspective. For example, consumer GPS devices often give turn-by-turn directions that convey information about upcoming route decisions using egocentric turn information (e.g., “turn right”). In addition, many devices use visual outputs that similarly reinforce a route perspective, such as mirroring the on-screen avatar's orientation with the navigator's, as is done in track-up GPS configurations. Thus the act of navigating and the aid's directions converge to promote route encoding of the novel environment. Most research has focused on navigational aids that deliver this type of information, presumably for high ecological validity. In contrast, spatial memory assessments often promote survey-perspective information retrieval, such as map drawing. Perspective switching between encoding and test evokes performance costs (Brunyé & Taylor, 2008; Shelton & McNamara, 2004). This cost may have contributed to previous results, although was not discussed as such.

Goal-directed learning, which can involve spatial perspective, is another spatial cognitive concept not previously accounted for. Navigational aids support efficient and accurate navigation between locations, but are rarely used outside of this context (e.g., exploring a new city). Understandably, previous navigational aid experiments have primarily used navigational goals. Yet, spatial cognitive studies have demonstrated that goal-directed navigation influences the resultant spatial representation (Brunyé & Taylor, 2009; Taylor & Naylor, 2002; Taylor et al. 1999). Learning goals, which for navigational aids tend to be bound to the route perspective, can highlight perspective-relevant information during navigation and influence later memory (Taylor et al., 1999), further reinforcing route encoding. Therefore, navigational goals in previous research may have promoted a more route-based mental representation.

Information Format

Another important spatial cognitive concept largely unexplored by previous research is the information format of navigational aid instructions. Typical navigational aids rely heavily on verbal route information. Such reliance is unsurprising given they are often used in attention demanding situations, such as driving. In this context, a solely visually-based aid could endanger navigators, and those around them, by drawing too much visual attention away from the road. Further, both map study and navigation are cognitively complex tasks that load working memory (Garden, Cornoldi, & Logie, 2002). Previous work has not considered whether verbal route information may similarly divide attention to an extent greater than would be intuitively expected through working memory interference.

According to Baddeley's working memory model (Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Baddeley, 2002), working memory is made up of several specialized components, including an auditory-verbal component, the phonological loop, and a visuospatial component, the visuospatial sketchpad. Verbal information is frequently used to represent spatial information, such as when naming landmarks or giving route directions. Thus, verbal working memory (VWM) and the phonological loop may subserve spatial memory. Corroborating evidence from dual task experiments, where participants navigate environments or read spatial texts while concurrently performing a secondary task, suggests that

VWM plays an important role in route learning (De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005; Garden et al., 2002; Pazzaglia, De Beni, & Meneghetti, 2007) and building spatial mental representations (Gras, Gyselinck, Perrussel, Orriols, & Piolino, 2013). These experiments support a dual-coding approach of wayfinding knowledge where spatial knowledge can be encoded and mentally represented in both spatial and verbal formats (Meilinger, Knauff, & Bulthoff, 2008). Therefore, the verbal route directions used in navigational aids may selectively interfere with phonological loop processing used in route learning. This selective interference of VWM would reduce environment encoding and consequently lead to a deficient mental representation. Previous research using auditory navigational aids has primarily relied on aids that present instructions verbally. Given the relationship between VWM and spatial memory, it is unclear whether the spatial memory impairments observed in these experiments arose from selective working memory interference from the verbal information format or from general attention shifts.

Motivation for Experiment 1

Experiment 1 explores how different navigational aids affect both navigational efficiency and spatial memory. In doing so, it extends nascent research on navigational aids by considering both previous explanations and additional spatial cognitive considerations. First, this study examines spatial perspective switching as an explanation for previous findings, by including the retrieval perspectives in the learning perspective. Second, it considers the role of information format on demonstrated costs of navigational aids on spatial memory. Lastly, by virtue of its design, Experiment 1 can qualify and extend proposals implicating spatial decision making and attention to account for how navigational aids impair spatial memory.

In addition to assessing influences of navigational aids on spatial memory, Experiment 1 examines how different aid modalities affect navigational efficiency. This is important to consider for several reasons. First and foremost, people use navigational aids to navigate efficiently. Aids provide direct routes that lead the user to their destination quickly and easily. Second, navigation performance affects one's degree of environmental exposure, which can in turn affect spatial memory. Experiment 1 examines navigational efficiency and spatial memory using desktop virtual environments (VEs).

Desktop VEs are an excellent tool for this research because they provide a somewhat realistic analogue to real navigation while allowing for controls of both navigation and environment features (Loomis, Blascovich, & Beall, 1999; Péruch & Wilson, 2004; Ruddle et al., 1997). Moreover, virtual navigation can provide high fidelity data, outputting quantitative measures of navigators' position and orientation, for accurate assessments of navigation. Further, as a control for variation in spatial ability, Experiment 1 employs a within-participants design. The majority of VE research has used between-participants designs with matched groups. However, wide variability (Hegarty, Waller, & Miyake, 2005) makes matching difficult.

To address spatial perspective switching concerns, Experiment 1's navigational aid and post-navigation spatial memory assessments promote mixed spatial perspective. Rather than give turn-by-turn directions, which reinforce the route perspective, the aids relay information about relative bearing and proximity to the goal location. As such the navigator receives information about the goal location, but is not explicitly directed to it, promoting survey perspective environment encoding. Further, because the aid presents this survey information through body-relative egocentric instructions (e.g. forward, to the right, etc.) it reinforces a within-environment view. Likewise, the spatial memory assessments promote both survey and route perspective retrieval. Participants must draw a map of the navigated environment, a task that requires them to represent the environment from the survey perspective. Participants must also complete an assessment that necessitates route perspective representation, virtual pointing. This task embeds participants at ground level within the environment and utilizes the same information and perspectives imparted by the navigational aids. Thus together map drawing (survey) and virtual pointing (route) measure spatial memory using a mixed spatial perspective. In contrast to previous navigation aid studies, the information imparted by the navigational aids does not specifically reinforce a route perspective, as turn-by-turn directions presumably do. Rather, by mixing spatial perspectives during both encoding and retrieval, this experimental design minimizes perspective-switching costs.

Experiment 1 specifically explores possible verbal interference by using two navigational aids, one verbal and the other tonal. These aids present roughly equivalent orientation and proximity information using different formats. The verbal aid does so via verbal information and the tonal aid uses binaural localized audio based on a real-time updated homing tone. Binaural audio is excellent for this application because it can accurately relay spatial sources using naturally-occurring, subtle timing and amplitude differences between ears. Several studies have demonstrated the utility of localized audio for navigational aids (Cohen, Fernando, Nagai, & Shimizu, 2006; Holland, Morse, & Gedenryd, 2002; Klatzky, Marston, Giudice, Golledge, & Loomis, 2006; Gunther, Kazman, & MacGregor, 2004; Lokki & Grohn, 2005; Loomis, Golledge, & Klatzky, 1998; Simpson et al., 2005). Further, given its non-verbal presentation of spatial information, it is assumed that the tonal aid recruits the visuospatial sketchpad rather than the phonological loop. This assumption is in line with Baddeley and Lieberman's (1980) finding that tracking sound location in space is assigned to the visuospatial sketchpad. By comparing performance when using verbal and tonal aids (and no aid), contributions of verbal information processing to spatial memory can be assessed.

Previous research has suggested three factors contributing to spatial memory impairments with navigation aid use: decreased environmental engagement, decreased spatial decision making, and increased divided attention. Experiment 1 considers the latter two of these proposals in its design. Because the navigational aid provides piloting information rather than explicitly directing the navigator, it does not eliminate spatial decision making during navigation. Participants know the target location's general direction and distance from their present position, but still have to decide how to get there. Thus we can observe whether our spatial memory results are consistent with previous findings implicating spatial decision making. Second, by including a tonal navigational aid we can further understand the role of attention. At present it is unclear how navigational aids divide attention. They may do so either by requiring attentional shifts to process incoming information or by loading working memory, specifically VWM. Localized binaural audio may provide a more direct perceptual path to encode spatial location (Begault, 1994; Carlile, 1996). Previous navigational aid research comparing localized audio and verbal audio suggests that localized audio places less demand on working memory than spatial language, which requires cognitive mediation (Giudice, Marston, Klatzky, Loomis, & Golledge, 2008; Klatzky et al., 2006). Since active maintenance and updating of information in working memory recruits attentional processes (Awh & Jonides, 2001; Awh, Vogel, & Oh, 2006; Olivers, 2008) the verbal aid may divide attention to a greater extent due to the working memory demands of processing spatial language.

Experiment Summary and Hypotheses

In Experiment 1, for each VE, participants first briefly studied an overhead view of the environment and then navigated it aided by either a verbal aid, a tonal aid, or without additional aid (control). Briefly studying the environment prior to navigation allowed participants to begin each condition with functionally equivalent prior knowledge. Therefore, in each experimental condition participants had some familiarity with the environment. This design consideration prevented participants, when in the control condition, from spending far more time navigating than when in the aided conditions. Increased navigation and environment exposure could contribute to spatial memory differences. Thus studying an overhead view of the environment prior to navigating allowed for direct spatial memory comparison between the aided and control conditions, but it also limited the interpretation of the results, as discussed later. The VEs were matched for approximate size, number of landmarks, and environmental complexity. Participants navigated in a goal-directed manner between 10 successive landmarks. After navigating, participants completed spatial memory assessments. We predict that the navigational aids will affect navigation and spatial memory differently. First, we predict that aided navigation will be more efficient than control. As the tonal and verbal aids provide roughly equivalent information, we predict no navigation differences between the two aids. Regarding spatial memory, we first predict aided navigation will impair spatial memory, consistent with previous findings. As the present aids did not reinforce certain spatial perspectives, this result would suggest that any spatial memory impairments are due to unique features of navigational aids and not simply an artifact of perspective-switching costs. We offer conditional predictions for spatial memory differences between the aid conditions. Should VWM interference underlie spatial memory impairments with navigational aids, we predict that the verbal aid will impair spatial memory to a greater extent than the tonal aid. This result would suggest that the verbal aid's working memory load recruits additional attentional processing. If, however, the aids impair spatial memory through general attentional shifts, we predict no differences between aid conditions.

Methods

Participants and Design

Thirty-six male Tufts University undergraduates (age *M* = 19.5) participated for monetary compensation. We recruited only males to control for gender differences in cue utilization during VE navigation (Astur, Ortiz, & Sutherland, 1998; Chai & Jacobs, 2010). All participants possessed normal or corrected-to-normal hearing. The study used a within-participants design with three levels of navigational aid type (Verbal, Tonal, None). To minimize order effects, we fully counterbalanced aid type and environment type across participants; this process resulted in 36 unique aid and environment combinations (3! x 3! = 36), one per participant.

Materials

Virtual Environments. We designed three realistic, large-scale desktop VEs using a commercially available video game editor (Unreal Engine 2 by Epic Games, Raleigh, NC). The environments were equated across several features. Each environment measured approximately 736,000 square feet and contained 16 unique and generic landmarks (e.g. Bank, Shopping Mall, Laundromat, etc.). Landmark signs were uniformly sized and clearly labeled with large black lettering over a white background. A red flag, placed at the front of each landmark, marked it as a navigation destination. Only areas between buildings were navigable; participants could not enter buildings. Avatar height was 1.76m and avatar movement speed was 8.8m/s. Walking from one corner of the environment to its opposite corner along the most efficient path took approximately 1 minute. Participants navigated the environments on a 20 in. widescreen LCD monitor at 1680x1050 resolution with a simulated field of view (FOV) of 90° and sat at a viewing distance of approximately 2 feet. Participants used a standard keyboard (W - forward, S- backwards, A & D, strafe left and right, respectively) to control movement and a mouse to control orientation. Other movement types inherent in the software, including jumping, crouching, and weapon use, were disabled.

We designed the navigation trials in each environment such that when participants navigated along the optimal paths between the sequential trials they passed in sight of all the landmarks in the environment. The VE software sampled avatar coordinate position (x, y, z) and orientation (roll, pitch, yaw) at 50 ms intervals. Figure 1 depicts a ground level view from one VE. Figure 2 presents overhead views of the three environments (VEs 1 - 3).

Navigational Aids.

Verbal Aid. Eight verbal recordings provided directional information. We synthesized these using the freely-available AT&T Voice Synthesizer (AT&T, 2011). The recordings corresponded to the eight azimuths that equally divide the 360 degrees of rotation around the navigator (e.g. 0°, 45°, 90° ... 315°). Figure 3 depicts these azimuths and their corresponding directions. In similar fashion, eight recordings provided distance information. These recordings corresponded to eight approximate distances the navigator could be from the goal in 100-foot increments (e.g. "100 ft., 200 ft., ... 800 ft."). Custom software presented these recordings during navigation, updating the commands in real time as the participant progressed through the environment. To accomplish this the software processed the participant's position and orientation data from the VE. Using this data, it calculated the participant's distance from and orientation relative to the current navigation goal. Lastly it relayed this information via a verbal recording presented through closed-ear headphones every five seconds. The recordings presented the directional information immediately followed by the distance information (e.g. "Slightly to the left, 400 feet."). When the participant reached the navigation goal, the software immediately presented a new navigation command, resetting the 5-second inter-recording timer.

Tonal Aid. The tonal aid relayed similar information as the verbal aid, but formatted differently. To denote orientation to the goal the software presented a tone emitting from the specified orientation. For example to represent "to the right" it would present a tone synthesized from 90° azimuth. To denote proximity to the goal the software adjusted the tone’s volume level in equal increments corresponding to the eight approximate distances (e.g. "100 ft., 200 ft., ... 800 ft.). It accomplished this by adjusting the system volume in increments of two (range: 2 - 16). Volume increased as proximity to the goal increased with the tone being loudest (16) at the nearest proximity to the target.

To create localized audio for the tonal aid, we used binaural audio. Binaural audio is well suited for this application because of its ability to represent sound sources in virtual space (Burgess, 1992). Binaural audio is typically recorded from small omnidirectional headphones placed inside the ears (see Møller, 1992 for review). Such recordings accurately represent an individual's unique head-related transfer function (HRTF), which models how different physical components (e.g. head, ears, neck, etc.) filter incoming sounds (see Carlile, 1996; Cheng & Wakefield, 2001 for review). This method is prohibitively impractical for experimental use, however, requiring recordings for each participant in an anechoic chamber. Sound synthesis provides a simpler means to produce such recordings. Software can convolve a sound signal with a HRTF, creating personalized localized audio. Experiment 1 employed this method using binaural audio synthesized from a publicly available database of HRTFs.

Eight binaural recordings providing directional information were synthesized using the Listen online HRTF database, which contains anthropometric data for 49 subjects and MATLAB scripts to both produce their corresponding HRTFs and create localized tones (Warusfel, 2003). For each subject in the database we synthesized 8 tones for a total of 392 recordings using the available MATLAB scripts. The recordings were modulated pink noise (modulation freq = 20Hz, duration = 1 sec). In contrast to white noise, which has a roughly equal distribution of energy across all frequencies, the energy of pink noise is inversely proportional to its frequency and consequently has decreased energy at higher frequencies. As a result, pink noise maintains a broad frequency spectrum while sounding less harsh than white noise (Walker & Lindsay, 2006). As with the verbal recordings, the tonal recordings corresponded to the eight azimuths that equally divide the 360 degrees of rotation around the navigator (e.g. 0°, 45°, 90° ... 315°) presented at zero degrees elevation (e.g. directly at ear level).

To semi-personalize the synthesized binaural audio for each participant we used a matching procedure detailed by Zotkin, Duraiswami, Davis, Mohan, and Raykar (2002). This procedure matches the participant's pinnae measurements to those in the HRTF database. In an exploratory study Zotkin, Duraiswami, and Davis (2004) found that semi-personalized HRTFs resulted in increased localization performance relative to a generic HRTF. In addition to the pinnae, other anthropometric measures contribute to individual variation in HRTFs (Carlile, 1996), particularly head width (Algazi, Duda, Thompson, & Avendano, 2001; Duda, Avendano, & Algazi, 1999; Kuhn, 1977; Middlebrooks, 1999). As such our matching procedure also considered head width. Custom software compared each participant’s pinnae measurements and head width to each HRTF database subject using error calculations detailed by Zotkin et al. (2004). The database subject with the lowest aggregate error term (and thus the corresponding binaural recordings) was selected as the best match for our participant. For more detailed description of the matching procedure see Appendix A.

Questionnaires. Questionnaires assessed factors known to contribute to virtual navigation success, including video game experience and spatial ability/preference differences. To assess video game experience, we used a common video game questionnaire (Basak, Boot, Voss, & Kramer, 2008). Overall, participants reported low-moderate video gaming frequency (M = 2.2 hours per week). To assess individual differences in spatial ability we used the Santa Barbara Sense of Direction Scale (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). We also used Pazzaglia and De Beni’s (2001) spatial representation questionnaire that assesses relative preference for landmark, route, and survey-based spatial representation. Overall, participants reported moderate sense of direction (*M* = 4.4 on a scale of 1 - 7). 20 participants reported route preference and 16 participants reported survey preference.

Procedure

Training. After obtaining informed consent, the experimenter measured participants' head width and pinnae. Participants then completed the questionnaires, administered by SuperLab software. The experimenter used custom software to find the best match from the HRTF database and loaded the matched binaural audio files. Upon completion of the questionnaire, participants completed the navigational aid training, also implemented via SuperLab. This training task was divided into two sections. The first section trained participants to recognize directional information from the navigational aid. It first presented images depicting the eight possible directions (e.g. forward, to the right, etc.) around the head and the corresponding verbal and tonal audio. Then it tested participants' understanding by presenting 96 audio-image pairs in random order, half of which were correct pairings. Participants responded, using the keyboard, whether the pairing was correct. They were required to achieve at least 80% accuracy. If they failed to reach criterion they were retested. The second section trained participants to recognize distance information from the navigational aid using an identical procedure. It presented images depicting the eight possible distances (e.g. 100 ft., 200 ft., etc.) and the corresponding verbal and tonal audio. Tonal recordings used in this section were localized in front of the participant (0°

azimuth) and varied in volume to denote distance. Upon completion of the navigational aid training, participants navigated two practice VEs to learn the navigation controls, one with each navigational aid.

Experimental Sessions. During an experimental session, participants first studied an overhead view of the VE for one minute. They then followed onscreen instructions (e.g. "go to the bank") to navigate between pre-defined, fixed-order sets of landmarks. Appendix B presents the ordered landmark sets for each VE (1 - 3). Participants completed ten navigation trials in their assigned navigational aid condition. Following navigation, participants completed landmark recall, listing all landmarks they could remember in five minutes. Then they completed two additional mixed spatial perspective spatial memory assessments, the order of which was counterbalanced. The first, virtual pointing, was run within the VE. This route-based task embedded participants in random locations in the environment (without repetition), instructing them to point to landmarks not visible from their location. Avatar translational movement was disabled and participants responded by rotating their orientation with the mouse and clicking to point. The second survey-based task instructed participants to spend 5 minutes drawing a map of the environment on a 8.5" x 11" paper. Participants completed three test sessions, one for each aid condition, separated by at least four hours to prevent carryover effects.

Coding

Navigation Analysis Software. Custom software analyzed participants' navigation data. The critical measure reported here is path efficiency, which relates the participant's actual path length (PLa) to the optimal path length (PLo) between a starting and a target location (PLo/PLa). This measure has a maximum value of 1 and a minimum value infinitely approaching 0. Higher values indicate greater efficiency. Previous research using this software has demonstrated that path efficiency is a reliable measure of navigational efficiency (Brunyé, Gardony, Mahoney, & Taylor, 2012; Gardony, Brunyé, Mahoney, & Taylor, 2011).

Virtual Pointing Analysis Software. Custom software analyzed participants' virtual pointing data. The critical measure reported here is pointing error, which represents the angle between the participant's pointing vector and the straight-line vector between the starting location and target landmark. This absolute error measure has a minimum of zero and a maximum of 180 with lower error indicating more accurate pointing.

Map Drawing Analysis Software. Custom software analyzed participants' hand-drawn maps. The critical measures reported here can be conceptually divided into two groups. The first group, containing canonical organization and canonical accuracy, *categorically* evaluates landmark placement. The second group, containing distance accuracy and angle accuracy, *metrically* evaluates landmark placement.

With the categorical measures, canonical organization was calculated by first comparing each landmark's position relative to all other landmarks using canonical directions (NSEW). Each of the 16 landmarks were compared to one another by considering both North vs. South (e.g. landmark 1 is north of landmark 2) and East vs. West (e.g. landmark 1 is east of landmark 2) directionality. The 16 landmarks resulted in ${}_{16}C_2 = 120$ combinations that were used for both North/South and East/West comparisons, totaling 240 comparisons. The program then compared the observed 240 canonical relationships on the hand-drawn map with the actual relationships within the environment. A correct comparison received one point and an incorrect one received zero points. Importantly, comparisons to a landmark missing from the hand-drawn map were automatically scored as zero. The sum of scores (x) divided by the number of comparisons (240) is the canonical organization score. This proportional measure ranges from 0 to 1 with higher scores indicating better organization and recall.

Canonical organization is limited by its treatment of missing landmarks. If, for example, a participant omits several landmarks, their canonical organization score drops quickly due to automatic zero-scoring of missing landmarks. In addition, a participant may have omitted several landmarks, but accurately arranged those depicted. To address these concerns the software calculated a second map drawing measure, canonical accuracy. While canonical organization considers the hand-drawn map in its entirety, canonical accuracy assesses participant’s spatial knowledge of remembered landmarks. Instead of zero-scoring combinations containing missing landmarks, canonical accuracy omitted them from the score calculation. Thus points were awarded based on combinations containing landmarks the participant had drawn. Canonical accuracy uses the same formula as canonical organization but reduces the denominator as it removes missing combinations. This proportional measure ranges from 0 to 1 with higher scores indicating better spatial organization.

While useful for evaluating the relative placement of landmarks, a downside of these categorical measures is their lack of fine-grain resolution. For example, a landmark may be correctly placed to the north and west of another landmark, but its absolute placement may be far from correct. The metric measures address this need by comparing participants' landmark placements to the actual environment. These measures neither considered nor scored missing landmarks. Formulae are presented in Appendix C. The first, distance accuracy, compared the distances between landmark combinations on the participant's map (observed) to those in the actual environment (actual). Observed distances were first scale-equalized by dividing by the largest distance between two landmarks on the participant's map. Using the same procedure, distance ratios were calculated for the actual environment. For each landmark comparison, the actual distance ratios were subtracted from the observed ratios. The sum of the absolute value of these difference scores was then divided by the total number of comparisons. Lastly, this error score was subtracted from 1. This proportional measure ranges from 0 to 1 with larger scores indicating better distance estimation.

The second measure, angle accuracy, compared the angles (range: -180 - +180) between the landmark combinations on the participant's map (observed) to those in the actual environment (actual). As with distance accuracy, the actual angles were subtracted from the observed angles for each landmark comparison. The sum of the absolute value of these difference scores was first divided by 180 and then by the total number of comparisons. Lastly, this error score was subtracted from 1. This proportional measure ranges from 0 to 1 with larger scores indicating better angle estimation.

The software analyzed participants' maps using these measures. Because participants navigated without knowledge of canonical direction, participants' maps were rotated until the software obtained the highest canonical organization score. All scoring then used this orientation.

Relationship of Map Analysis to Bidimensional Regression. The software's analysis method shares important similarities and notable differences with bidimensional regression. Bidimensional regression is a well-known statistical technique that assesses the configurational accuracy between two or more sets of points in a 2D plane (Friedman & Kohler, 2003; Tobler, 1994). It offers several advantages in the analysis of hand-drawn maps. The correlation coefficient, r, measures the degree of resemblance between sets of configurations of points. Importantly, this coefficient is insensitive to scaling, translation, and rotation. Consider two identical configurations of points, Set 1 and Set 2. Set 2 may have distances between each point that are increased by some constant magnitude relative to Set 1 (scale). Set 2 may also be translated in 2D space relative to Set 1 (translation). Lastly, Set 2 may be rotated by some angle relative to Set 1 (rotation). In all cases and combinations, provided the configurations between Sets 1 and 2 are identical, the correlation coefficient will remain 1.

Bidimensional regression also produces parameters that measure the extent to which Set 2 is scaled, translated, and rotated relative to Set 1.

The present map analysis technique shares some of these advantages. The metric measures (distance and angle accuracy) are insensitive to scaling and translation. Distance accuracy is calculated through distance ratios which scale all inter-landmark distances to the largest distance in their map, scale-equalizing the participant's map with the actual environment map. Further, because this measure only deals in inter-landmark distances, neither translation nor rotation of the configuration influences the measure. Angle accuracy is likewise insensitive to scaling and translation but is sensitive to rotation, a disadvantage compared to bidimensional regression. However, the present environments and hand-drawn maps were generally square so it is unlikely that this sensitivity to rotation confounded the data or interpretation.

The present technique also does not provide parameters for scaling, translation, and rotation, as bidimensional regression does. Nevertheless, the present technique offers a novel advantage in its handling of missing landmarks. Canonical organization zero-scores landmark comparisons containing a missing landmark, providing a measure of map completeness. Bidimensional regression requires that both the participant's map and the environment have the same number of landmarks and thus cannot provide such a measure.

Results

Navigation Performance

For the following analyses, we used repeated measures analysis of variance (ANOVA). In the case of sphericity violations we used the Greenhouse-Geisser correction (Geisser & Greenhouse, 1958), denoted by F_{GG}. Follow-up analyses consisted of simple effects contrasts comparing aid conditions to control and used Bonferonni-corrected alphas.

Path Efficiency. To examine navigation performance over time, we averaged data into five trial groups. Recall that participants navigated 10 sequential, fixed-order navigation trials. Trial group 1 contained data only for trial 1. At trial 1, participants could not have acquired navigation-based information and as such is unique. With this trial we can examine differential effects of the navigational aids on initial navigation. The remaining four trial groups combined trials into roughly equal groups as follows: trial group 2 contained trials 2-3, group 3 grouped trials 4-5, group 4 contained trials 6-7, and group 5 combined trials 8-10. We submitted path efficiency data to a 3(Aid Type: Verbal, Tonal, None) x 5(Trial Group: 1, 2, 3, 4, 5) repeated measures ANOVA. There was a main effect of Aid Type, $F(2,70) = 7.21$, $p = .001$, $\eta_p^2 = .171$. Follow up contrasts revealed that navigators in both the verbal aid, $F(1,35) = 10.03$, $p = .003$, $\eta_p^2 = .223$, and the tonal aid conditions, $F(1, 35) = 9.68$, $p = .004$, $\eta_p^2 = .217$, demonstrated higher path efficiency than control. Analysis also revealed a main effect of Trial Group, $F_{GG}(2.58, 90.2) = 15.08$, $p < .001$, $\eta_p^2 = .301$. Follow up contrasts revealed higher path efficiency in trial groups 3, $F(1,35) = 18.43$, $p < .001$, $\eta_p^2 = .345$, 4, $F(1,35)$

$= 31.36, p < .001, \eta_p^2 = .473$, and 5, $F(1,35) = 21.8, p < .001, \eta_p^2 = .384$, relative to group 1. The main effects were qualified by an Aid Type by Trial Group interaction, $F_{GG}(5.77,201.91) = 2.56, p < .05, \eta_p^2 = .068$ (see Figure 4 and Table 1).

To investigate path efficiency differences between aid conditions in each trial group we ran separate repeated measures ANOVAs (Aid Type: Verbal, Tonal, None). Analysis revealed a main effect of aid type in trial group 1, $F(2,70) = 12.92, p < .001, \eta_p^2 = .144$. As shown in Figure 4 and Table 1, during the first trial, navigators in the verbal aid condition demonstrated higher path efficiency than control, $F(1,35) = 10.87, p < .01, \eta_p^2 = .237$. In all other trial groups, no significant differences emerged.

Spatial Memory

For the following analyses, we used repeated measures multivariate analysis of variance (MANOVA). The MANOVA included the following measures, which are grouped by task for clarity: *Virtual Pointing Measures*: pointing error, response time; *Landmark Recall Measure:* number of landmarks recalled; *Map Drawing Measures*: canonical organization, canonical accuracy, distance accuracy, angle accuracy. The multivariate result indicated a significant effect of aid condition, $F(14,22) = 3.26, p < .01, \eta_p^2 = .674$. Univariate tests showed differences by aid condition for pointing error, $F(2,70) = 10.77, p < .001, \eta_p^2 = .235$, landmark recall, $F(2,70) = 13.84, p < .001, \eta_p^2 = .283$, canonical organization, $F(2,70) = 12.67, p < .001, \eta_p^2 = .266$, canonical accuracy, $F(2,70) = 4.26, p < .05, \eta_p^2 = .109$, and angle accuracy, $F(2,70) = 3.45, p < .05, \eta_p^2 = .09$. As shown in Table 2, the pattern of result was identical across these measures. Both aid conditions led to worse spatial memory than control and there were no differences in spatial memory between the two aid conditions. No significant effects emerged for pointing response time and distance accuracy (all p's > .05). However, the distance accuracy means trended in the same direction as the other measures.

We further examined if the layout of each environment influenced spatial memory. We submitted the spatial memory data from the control condition to a one-way between-participants MANOVA (Environment Number: 1, 2, 3). The MANOVA revealed no memory differences between the three environments, $F(14,56) = 0.66$, $p > .1$.

Individual Differences

Analysis revealed no correlations between the individual difference measures and navigation and spatial memory data. Further, when the measures were categorically coded (e.g. high vs. low sense of direction, etc.) no main effects or interactions were found (all p's > .1).

Discussion

Experiment 1 examined how different navigational aids affect navigational efficiency and whether specific aspects of these aids contribute to their negative effect on spatial memory. Navigational aids had different effects on navigational efficiency and spatial memory. Consistent with our prediction, aided navigation was more efficient than control. When comparing the aids, participants navigated more efficiently with the verbal aid, compared to control, early on, but this difference was not observed with the tonal aid. Interestingly, the positive effects of a navigational aid on navigational efficiency were short-lived. Differences between aided and control navigational efficiency disappeared as early as the second and third navigation trials (trial group 2). These results demonstrate that navigational aids can make navigation more efficient, but only initially when the navigator has had little exposure to the environment.

A different story emerges from the spatial memory data. Results resoundingly suggest that navigational aids, regardless of type, impair spatial memory. This result has been shown previously (Burnett & Lee, 2005). We further asked whether the spatial memory impairments of navigational aid use could be attributed to selective interference in VWM and/or general divided attention. The two navigational aid types allowed us to examine the selective interference explanation. If the information format of the navigational aids selectively interferes with VWM, we would expect greater spatial memory impairments for the verbal aid. In contrast, a divided attention explanation should yield general memory impairments, with no differences between our aid conditions. Converging evidence from landmark recall, virtual pointing, and map drawing demonstrated a general spatial memory impairment. In contrast to the navigation results, aid type did not modulate this effect. As such our data are consistent with a divided attention explanation (Fenech et al., 2010) and do not support a selective VWM argument. Here we discuss how our findings extend previous research on navigational aids and spatial memory.

Navigation

Our navigation data provide insight into the utility of navigational aids when navigators have some prior environmental knowledge. Recall that participants studied an overhead view of the environment for one minute. This was necessary to provide some environment information prior to navigation. Allowing participants to navigate naive to the environment would result in differential environment exposure between aided and control navigation. Control navigation would take far longer than aided, leading to more time spent navigating, more opportunity for environmental encoding, and could, consequently, account for better spatial memory. The interaction between aid type and trial group with our path efficiency data revealed that only in trial 1 did differences in navigational efficiency between the experimental conditions emerge. This finding confirmed that Experiment 1's design accounted for this potential confound. Thus our spatial memory results cannot be explained by differential environment exposure across conditions.

The utility of navigational aids when navigators have some advanced knowledge is limited. Analysis of path efficiency by trial group revealed that participants initially navigated efficiently with the verbal aid, but this difference did not persist in later trials. Rather, as navigation progressed, the verbal aid maintained a near constant level of efficiency while the tonal and control condition's efficiency improved rapidly. This indicates that navigators with some initial environment knowledge can quickly build accurate spatial mental representations that then assist navigation as well as navigational aids. These findings cast doubt on the utility of navigational aids when there is some preexisting knowledge of the environment. If navigational aids do not support more efficient navigation than mental representations in somewhat familiar environments, perhaps users are drawn to these technologies for other reasons. Aids may provide navigators with other benefits such as increased peace of mind or reduction in anxiety during navigation. However, such discussion is beyond the scope of this thesis.

Spatial Memory

Our results also extend and qualify emerging explanations to account for how navigational aids impair spatial memory. Here we discuss two that have been recently proposed. The first suggests that spatial decision making or deciding where to go during navigation is necessary for accurate environmental encoding (Bakdash, et al., 2008; Bakdash, 2010). The second posits that attention to the surrounding environment during navigation underlies accurate encoding (Fenech et al. 2010). In other words, by giving route directions, navigational aids forcibly disengage navigators' attention from their environment leading to encoding failure. Experiment 1's design sheds light on these arguments in the following ways.

First, the navigational aids did not completely eliminate the need for spatial decision making during navigation. Recall that the aids did not give turn-by-turn directions, which explicitly lay out an optimal path. Rather the aids presented general heading and distance information to goal locations. Routes in the environment did not necessarily correspond directly with the direction information. At times navigators chose between multiple route options, with some routes initially heading in a direction different from that indicated by the navigational aid. Thus participants still made spatial decisions during navigation and still had impaired memory. One interpretation of this finding is that spatial decision making does not play as important a role in spatial memory encoding during navigation as previously proposed. However, it is also possible that even partial removal of spatial decision making with the present aids was sufficient to impair spatial memory. Neither possibility can be confirmed from the Experiment 1's findings. However, future research could compare our navigational aid design in which spatial decision making is partially (but not completely) eliminated, to a turn-by-turn aid that completely removes spatial decision making. Such research could elucidate the role of spatial decision making in navigational aids and spatial memory.

Second, Experiment 1 extends findings implicating attention in navigational aids. In using localized binaural audio Experiment 1's tonal aid provides an information format presumed to load working memory to a lesser degree than the verbal format. We predicted the increased working memory load of the verbal aid would increase divided attention and thus worsen spatial memory relative to the tonal aid. However, this was not the case, as evidenced by equivalently poor spatial memory for the two navigational aids. Thus our results do not support an explanation of divided attention as a product of increased working memory load. Rather the present data suggest that both aids divided attention and information format did not further modulate the effect.

Strengths and Limitations

To our knowledge Experiment 1 is the first to consider and control for spatial perspective in the context of navigational aids and their influence on spatial memory. While previous studies reinforced a route perspective during learning, but tested memory with survey perspective tasks, Experiment 1 mixed spatial perspectives at encoding and test. At test, one task closely matched the information provided during navigation (virtual pointing) and the other was further removed, promoting survey perspective retrieval (map drawing). The closely matched performance on the two memory tasks rules out spatial perspective switching as a confounding factor.

Our sensitive measures of navigation and spatial memory further support our findings. By using desktop VEs, we provided a somewhat realistic analogue to real-world navigation while recording navigation behavior with high temporal and spatial resolution. We also employed novel techniques to assess spatial memory. In the virtual pointing task, participants pointed from randomized locations embedded in the VE. This task is similar to judgments of relative direction (see: Levine, Jankovic, & Palij, 1982; Shelton & McNamara, 1997) and provides a realistic task and sensitive measurement of spatial memory. Lastly, our map analysis technique is novel and able to measure several aspects of participants' maps, including overall organization and distance estimation using continuous metrics.

Despite these strengths, limitations constrain the interpretation of our results. First, the desktop VEs required no self-locomotion to navigate as other more immersive VE system do. These fully immersive systems, which often utilize head-mounted displays, motion tracking, and/or treadmill locomotion, provide proprioceptive and vestibular cues which impart a more immersive experience and a sense of "being there" (Ruddle, Payne, & Jones, 1999). Further, much research suggests that such idiothetic information plays an important role in spatial learning and memory (Chrastil & Warren, 2012). The lack of idiothetic information in Experiment 1's desktop VEs may partially explain the lack of a strong relationship between individual difference measures and navigation and spatial memory data.

Second, in order to provide functionally equivalent prior environmental knowledge between aid conditions, participants first briefly studied an overhead view of the environment prior to navigating it. While this design consideration allowed for direct spatial memory comparison between the aided and control conditions it does constrain interpretation of our findings. Here we have shown that navigational aids impair spatial memory in somewhat familiar environments but it is unclear if this finding generalizes to novel environments as well. Further, studying an overhead view of an environment is inherently a survey perspective task that likewise promotes survey encoding. As such, the experimental design may have "front-loaded" survey perspective encoding prior to navigation.

Third, our data suggest that navigational aids impair spatial memory by dividing attention and not through selective interference of VWM. This is apparent from the general impairment of spatial memory by the verbal and tonal aids and the lack of differences between the two aids. Nevertheless, both the tonal and verbal aid may interfere with VWM and the phonological loop. It is possible that participants recoded the information from the tonal as verbal during comprehension. For example, participants may have internally generated the word "right" when hearing a tone emanating from the right. In this case, both the tonal and verbal aid would have interfered with VWM and this could explain why there were no spatial memory differences observed between the two aids. At present we consider this unlikely given that a) participants were trained to associate the tones with non-verbal spatial directions and to consider them homing beacons and b) spatial audio engenders less working memory load than spatial language (Giudice et al., 2008). Nevertheless, due to Experiment 1's lack of post-experiment participant interviews, it is unclear if phonological coding of the tonal stimuli took place.

Fourth, though the simplified design of our navigational aids allows us to ask questions about specific aid components, it differs substantively from real-world navigational aids, reducing the ecological validity. Typical aids, such as consumer GPS, tend to confound many features, including visual information, verbal turn-by-turn directions, and alert tones. Therefore we cannot be certain that our manipulations may not interact with other features inherent in common navigational aids.

Lastly, we exclusively recruited males to avoid gender effects in cue utilization. This decision, however, limits generalizability of our results. Though cue utilization is important for effective navigation, our participant selection prevents analysis of gender effects, which have been noted in several spatial cognitive domains.

Future Directions

In extending previous findings, Experiment 1 suggests further research questions. The navigational aids impaired spatial memory despite allowing participants to make spatial decisions while navigating. Still, it is possible the present aids may have removed just enough decision making to negatively affect spatial memory. Future research should manipulate the amount of spatial decision making in navigational aids to clarify its contribution to spatial memory impairment. Regarding attention, Experiment 1's data do not support the selective working memory load induced divided attention argument, but do support the more general divided attention argument. Still, the mechanism by which divided attention drives spatial memory impairments is unclear. Experiment 2 will address this need by comparing spatial memory after navigation with an aid compared to a divided attention task. Further, though Experiment 1's results demonstrate no effect of spatial perspective or information format it is still possible that these features interact with others found on common and complex navigational aids, such as turn-by-turn aids. Lastly, the spatial memory assessments were insufficient to observe the time-course of spatial memory development. Using intermittent assessments or neuroimaging techniques to observe how spatial mental representation and spatial memory develop during aided navigation would be an excellent addition to this emerging area of spatial cognition.

Interim Summary

Consistent with previous research, Experiment 1 demonstrates that using navigational aids in somewhat familiar environments only marginally improves navigation and has large spatial memory costs. These costs seem unrelated to perspective switching costs (Brunyé & Taylor, 2008; Shelton & McNamara, 2004) or selective VWM interference. Rather, they appear to arise from general divided attention.

Motivation for Experiment 2

Spatial memory data from Experiment 1 do not support the selective working memory interference argument, but do support the more general divided attention argument. Further focused research is needed to confirm the mechanism by which divided attention drives navigational aids' spatial memory deficits. Experiment 2 addresses this need by comparing spatial memory after navigation with an aid compared to and crossed with a divided attention task. However, before describing how Experiment 2 examines divided attention's role in navigational aids, a review of relevant literature is needed.

Theoretical Background - Experiment 2

Attention underlies effective navigation and the formulation of accurate spatial mental representations. Indeed, vehicle passengers often report worse spatial memory relative to when they are the driver (Péruch & Wilson, 2004; Sun, Chan, & Campos, 2004; Wilson & Péruch, 2002; but see: Bakdash et al., 2008). In novel environments, navigators attend to environment components such as landmarks, decision points (e.g. intersections), and routes. They also invoke executive function to integrate these components into a configural mental representation. Previous research has demonstrated that the development of both survey and route knowledge is contingent on active attention during navigation (Albert, Reinitz, Beusmans, & Gopal, 1999; Anooshian & Seibert, 1996; Lindberg and Garling, 1982; Smyth and Kennedy, 1982). Certain aspects of environmental encoding do not require attention, however. For example, navigators can gain landmark knowledge incidentally, without attending to their route (Van Asselen, Fritschy, & Postma, 2006). Further, guiding attention to specific aspects of the environment, such as routes, can strengthen encoding of those aspects (Magliano, Cohen, Allen, & Rodrigue, 1995) or reinforce certain spatial perspectives (Taylor et al., 1999). Taken together, this research suggests that while some aspects of the environment can be encoded with little cognitive effort, gaining route and survey knowledge and a robust mental representation depends on attentional deployment (Chrastil & Warren, 2012).

Divided Attention and the Dual-Task Paradigm

An effective way to assess attention's role in specific cognitive processes is to divide attention. One frequently used method of dividing attention is dual-task interference. In such tasks, participants must respond to two simultaneous tasks, such as repeating a word while tapping a pattern. To do so effectively, participants must divide attention between the tasks (Braun, 1998; but see Damos, 1991). By dividing attention between two or more tasks or inputs, attentional allocation to the task of interest is interrupted. If the lack of consistent attention leads to task impairments it suggests attention is an important part of the task.

The relationship between divided attention and task performance may underlie navigational aids' spatial memory impairments. Previous research has shown that divided attention can lead to encoding failure and subsequent poor memory (Anderson, Craik, & Naveh-Benjamin, 1998; Baddeley, Lewis, Eldridge, & Thomson, 1984; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Murdock, 1965). This is important to consider given navigators often use navigational aids in attention-demanding contexts where degraded task performance carries heavy consequences. As such, designers of these systems have attempted to provide directional information in ways that minimally divide attention (Alm, 1993; Streeter, Vitello, & Wonsiewicz, 1985; Wierwille, Antin, Dingus, & Hulse, 1988). However, as both the observed spatial memory impairments from Experiment 1 and previous research (Burnett & Lee, 2005; Fenech et al., 2010) suggest, navigational aids may still divide attention, despite design considerations. Another possibility is that navigational aids do not impair spatial memory by dividing attention but rather through other distinct mechanisms. To address this question, Experiment 2 incorporates dual-task methodology by degrading the intelligibility of the aid commands and requiring participant response when unintelligible commands are presented.

Divided Attention and Working Memory

Dual-task methodology has been used in generating theories of working memory models. There it has formed the methodological basis for identifying the various components of Baddeley's working memory model (Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Baddeley, 2002). In their studies, Baddeley and colleagues used dual tasks to disrupt the individual components of their model, such as pattern tapping tasks to disrupt the visuospatial sketchpad (Baddeley & Lieberman, 1980), articulatory suppression to disrupt the phonological loop (Baddeley, Thomson, & Buchanan, 1975), and generating random digits to disrupt the central executive (Baddeley, Emslie, Kolodny, & Duncan, 1998).

The link between central executive processing and attentional control is of special interest. Baddeley and others have suggested that the central executive is responsible for dividing and/or switching attention (Baddeley, 1996; Baddeley, Baddeley, Bucks, & Wilcock, 2001; Baddeley & Logie, 1999; Bourke, Duncan, & Nimmo-Smith, 1996; Perry & Hodges, 1999). Further other researchers regard the central executive as an attentional system (Cowan, 1999; Engle, Kane, & Tuholski, 1999a). Taking this view, dividing attention may task the central executive and consequently the working memory system. Evidence from dual task experiments, where participants read spatial descriptions while performing secondary tasks that disrupt specific components of Baddeley's model, suggests that the central executive plays an important role in spatial mental model development (Brunyé & Taylor, 2008). During navigation, the central executive is important for selection and integration of verbal and visuospatial information as well as in monitoring sequential information. Such working memory findings offer a mechanism by which navigational aid use can impair spatial memory.

The links between working memory and divided attention further suggest that individual differences in working memory may contribute to the extent to which navigational aids impair spatial memory. Working memory capacity (WMC) (Engle, 2001) is an oft-cited measure of the extent to which an individual can control attention to maintain information in an active and quickly retrievable state. Engle and colleagues have shown that WMC has predictive validity for a wide range of cognitive abilities, including reading comprehension, learning, fluid reasoning, and general fluid intelligence (Daneman & Carpenter, 1980; Engle, 2001; Engle, Tuholski, Laughlin, & Conway, 1999b). In defining the construct, Engle (2002) stresses that high WMC does not reflect a large WM store. Rather, it reflects a greater ability to control attention and maintain information in the face of interference (Engle, 2001; Engle et al., 1999a; Engle et al., 1999b; Kane & Engle, 2000; Kane & Engle, 2002; Rosen & Engle, 1998). As such, in a divided attention task, an individual's WMC may predict how much the divided attention task impairs the main task. If navigational aids divide attention, then high WMC navigators may be better able to build a mental representation of the environment in face of the interference provided by the aid. To quantify how individual differences in WMC interact with divided attention, Experiment 2 measures WMC using the operation-span task (OSPAN) (Turner & Engle, 1989).

Experiment Summary and Hypotheses

Experiment 2 addresses the role of divided attention in navigational aids using a dual-task paradigm. Participants navigated four approximately equated desktop virtual environments (VEs) under four conditions. The conditions crossed aid presence with divided attention. As in Experiment 1, participants navigated in a control condition, in which no aid is present, and an aided condition, analogous to the verbal aid condition of Experiment 1. These two conditions crossed *undivided* attention with aid presence, absent and present respectively. The remaining two conditions represented the *divided* attention conditions. In the aid-absent condition, participants attended and responded to a divided attention task during navigation. In the aid-present condition, participants received aid during navigation but the aid was both difficult to hear and required responses, thus dividing attention. The factorial design can determine the role of divided attention in spatial memory impairment from navigational aid use. After navigation, participants completed spatial memory assessments.

We predict that aided navigation, regardless of divided attention, will be more efficient than control, consistent with Experiment 1. Regarding spatial memory, we predict a main effect of aid presence with worse spatial memory in the aid-present condition relative to the aid-absent. We also predict a main effect of divided attention with worse spatial memory when attention is divided relative to when it is not. For the interaction between aid presence and divided attention, we offer conditional hypotheses. For these hypotheses, the critical comparison considers the magnitude of spatial memory difference between the aid presence conditions within each divided attention condition.

Should navigational aids impair spatial memory solely through divided attention mechanisms, we hypothesize that aid presence will impair spatial memory when attention is undivided, as in Experiment 1, but not do so further when attention is divided. This finding would suggest that when attention is divided, a "threshold" for impairment due to divided attention will have been reached and aid presence would not further impair spatial memory. In line with this hypothesis, the impairment engendered by divided attention when aid is absent would be equivalent to the impairment engendered by aid presence when attention is undivided. This would suggest that aid presence alone and divided attention alone impair spatial memory to the same extent. Alternatively, should navigational aids impair spatial memory through distinct mechanisms, we hypothesize two possible outcomes. Aid presence may impair spatial memory equivalently across divided attention contexts, yielding main effects for both factors but no interaction between them. Alternatively, aid presence may further impair spatial memory when attention is divided, yielding an interaction. Either outcome would suggest a distinct mechanism that contributes to spatial memory impairment in addition to divided attention.

Methods

Participants and Design

Twenty-four Tufts University undergraduates (age $M = 21$, n male = 12) participated for monetary compensation. Experiment 2 used a 2 x 2 factorial within-participants design crossing Aid Presence (Present, Absent) and Divided Attention (Divided, Undivided), resulting in the following four experimental conditions: Clear Aid (Aid Present, Undivided Attention), Aid in Noise (Aid Present, Divided Attention), Control (Aid Absent, Undivided Attention), and Words in Noise (Aid Absent, Divided Attention). To minimize order effects, the order of the VEs and experimental conditions were counterbalanced in a Graeco-Latin Square, which resulted in 16 unique condition and environment combinations (4 per participant). Experiment 2's sample (n = 24) resulted in 6 participants in each of these 16 unique combinations.

Materials

Virtual Environments. Experiment 2 used the same three VEs from Experiment 1 and a new fourth environment. This environment was equated with the others in terms of size and number of landmarks (16). Figure 2 depicts the fourth environment. All other aspects of VE navigation were identical to Experiment 1.

Navigational Aids. Two experimental conditions reappear from Experiment 1: Control, where no navigational aid is given, and Clear Aid, which is identical to Experiment 1's verbal aid condition. The two new conditions, Aid in Noise and Words in Noise are described below.

Aid in Noise. The aim of this condition was to increase divided attention during aid use. To do so we embedded the aid commands in white noise to achieve near-chance comprehension. The eight verbal recordings from Experiment 1's verbal navigational aid (e.g. "forward," "to the right," etc.) were used to create the aid in noise. To determine how much noise was required to bring comprehension to chance levels and thus divide attention a pilot study was conducted (n = 12, *M* age = 20.4 years, 7 female). All participants reported normal hearing and did not wear hearing aids. Further, participants' self-reported hearing ability was assessed with the Speech, Spatial and Qualities of Hearing Scale (SSQ) (Gatehouse & Noble, 2004). Participants marked their responses on a 10-point Likert scale. Part 3 (Qualities of hearing) was most relevant to the pilot study and on this section participants reported good hearing quality (*M* = 7.06).

The verbal direction recordings were embedded in increasing levels of noise and their intelligibility was assessed in a pilot study. The recordings were embedded in white noise using the freely available Audacity software. For each of the five conditions the relative gain of the noise was increased by 6 dB increments resulting in five recording to noise ratios (0:0, 0:6, 0:12, 0:18, 0:24). These stimuli composed the intelligible group. A second group of stimuli was created in the same fashion except the recordings were reversed and therefore unintelligible. These stimuli composed the unintelligible group. Participants listened to the stimuli and judged their intelligibility. In the intelligible case, participants responded by pressing the keypad number corresponding to the direction the recording presented (e.g., 8 corresponded to forward, 6 to right, etc.). If the recording was unintelligible, participants pressed the "5" key. Chance performance on this task fell between the 0:12 stimuli (*M* hit rate = .87) and the 0:18 stimuli (*M* hit rate = .43). Thus, a 0:15dB recording to noise ratio was selected for the aid in noise.

As in Experiment 1, custom software presented these recordings during navigation every five seconds, updating the embedded-in-noise recordings in real time as the participant progressed through the environment. However, in contrast to Experiment 1, participants had to respond when they heard unintelligible commands. Approximately half the time the verbal recordings were reversed and therefore unintelligible. Participants were instructed to respond when they heard unintelligible recordings by pressing the spacebar during navigation. The software recorded participants' accuracy and response times for this secondary task.

Words in Noise. The aim of this condition was to divide attention but not provide aid to the navigator. A set of English nonsense phrases that corresponded to the commands used in the navigational aid was selected. The words in the nonsense phrases matched the length of those in the verbal commands. Further, to equate saliency, the words and commands did not significantly differ in log subtitle frequency, $t(37) = -1.91$, p = .06 (see Brysbaert & New, 2009 for review of subtitle frequency). Table 3 presents the phrases and their corresponding navigational aid commands. Note that "right" has several uses in English, both in spatial and non-spatial contexts, and as a result has high subtitle frequency. The closest frequency match to "right" ("thing") possessed a notably lower frequency. This matching difficulty contributed to the marginal t statistic in the analysis. As with the aid in noise, a pilot study (n = 6, *M* age = 19.5, 3 female) was conducted to determine a noise level that would bring comprehension to near-chance levels. All participants reported normal hearing and did not wear hearing aids. Participants also completed the SSQ and reported good hearing quality (*M* = 7.78).

The nonsense phrases were embedded in four increasing levels of white noise (0:9, 0:12, 0:15, 0:18). These stimuli composed the intelligible group with reversed phrases composing the unintelligible group. Participants listened to the stimuli and judged each for intelligibility, responding using the keyboard. Chance performance on this task arose for the 0:15dB stimuli (*M* hit rate = .5) and this recording to noise ratio was selected for the words in noise.

Custom software presented the embedded-in-noise phrases during navigation every five seconds. Approximately half the time the presented phrases were reversed and therefore unintelligible. Participants were instructed to respond when they heard unintelligible phrases by pressing the spacebar during navigation. The software recorded participants' accuracy and response times for this secondary task.

Individual Difference Measures. Experiment 2 reused Experiment 1 questionnaires, plus a new questionnaire, the Questionnaire on Spatial Strategies (FRS) (Münzer & Hölscher, 2011) which assesses individual preferences for spatial strategies. In addition, participants' working memory capacity was assessed by the OSPAN task (Turner & Engle, 1989). This task involves verifying simple mathematical statements while simultaneously remembering word lists.

Overall, participants reported low video game frequency (*M* = 1.78) and moderate sense of direction (*M* = 4.9 on a scale of 1 - 7). Participants were evenly split between survey and route preference. On the FRS (scale: 1 - 7), participants reported moderate global self-confidence (*M* = 4.4), moderate usage of survey strategies (*M* = 4.2), and low knowledge of cardinal directions (*M* = 2.6). Participants possessed moderate WMC (*M* = 33.5 on a scale of 0 - 60).

Procedure

Training. After obtaining informed consent, participants completed the questionnaires followed by the OSPAN, both administered by SuperLab software. Participants then completed the virtual navigation and navigational aid training. In this task, participants navigated a practice virtual environment to learn the navigational controls. They then repeated navigation using each of the four experimental conditions, gaining familiarity with and understanding of the task demands of each. Following that, the experimenter explained the spatial memory assessments and participants completed a practice virtual pointing task to learn the task's controls.

Experimental Sessions. Experimental sessions were very similar to those in Experiment 1 with a few notable differences. As in Experiment 1, for each VE, participants first studied an overhead view of the environment for one minute and then navigated between a set of 10 pre-defined, fixed-order sets of landmarks. For environments 1 to 3, these sets were identical to Experiment 1. Appendix B presents the ordered landmark set for environment 4. Following navigation, participants completed the same memory assessments as in Experiment 1:

landmark recall, virtual pointing, and map drawing. As before, landmark recall immediately followed navigation and virtual pointing and map drawing were subsequently presented in counterbalanced order. Participants completed four test sessions, one for each experimental condition. In contrast to Experiment 1, which separated each session by at least four hours, Experiment 2 separated sessions with a five-minute filler task to prevent carryover effects. We determined that Experiment 1's four hour separation was unnecessary and that this filler task was sufficient. Participants either took a break or tracked a moving ball displayed on a head mounted display and answering arbitrary questions about the ball.

Results

The data used in the following analyses were collected from participants (24/28) who met minimum performance criteria on the secondary tasks (Aid in Noise & Words in Noise conditions). We set these criteria in order to confirm that participants paid attention to the secondary tasks thus providing a manipulation check for the divided attention manipulation. For these tasks we defined a "hit" as correctly responding when the embedded phrase/commands were unintelligible. Participants in the present data set possessed hit rates greater than 5% for both secondary tasks. Despite this relatively low cutoff, hit rates were generally higher (Aid in Noise: $M = .58$, Words in Noise: $M = .33$).

Navigation Performance

For the following analyses, we used repeated measures analysis of variance (ANOVA). In the case of sphericity violations we used the Greenhouse-Geisser correction (Geisser & Greenhouse, 1958), denoted by F_{GG}.

Path Efficiency. To examine navigation performance over time, as before we averaged data into five trial groups, as in Experiment 1, with trial group 1 containing only trial 1 and trial groups 2 - 5 dividing the remaining 9 trials into roughly equal groups. We submitted path efficiency data to a 2(Aid Presence: present, absent) x 2(Divided Attention: divided, undivided) x 5(Trial Group: 1, 2, 3, 4, 5) repeated measures ANOVA. Divided attention led to decreased navigational efficiency relative to undivided, $F(1,23) = 22.58$, $p < .001$, $\eta_p^2 = .495$. Interestingly, neither a main effect of aid presence nor interactions emerged, all *p*'s > .1. Figure 5 depicts the path efficiency data. Table 4 presents means. Analysis also revealed a main effect of Trial Group, $F_{GG}(2.31,53.22) = 8.74$, $p < .001$, $\eta_p^2 = .495$. Follow-up contrasts revealed higher path efficiency in trial groups 2, $F(1,23) = 4.9$, $p = .04$, $\eta_p^2 = .176$, 3, $F(1,23) = 8.32$, $p = .008$, $\eta_p^2 = .266$, 4, $F(1,23) = 11.49$, $p = .003$, $\eta_p^2 = .333$, and 5, $F(1,23) = 19{,}87$, $p < .001$, $\eta_p^2 = .464$, relative to group 1.

We further conducted follow-up analyses to investigate path efficiency differences within each trial group. We ran separate 2(Aid presence: present, absent) x 2(Divided attention: divided, undivided) repeated measures ANOVAs for each trial group using a Bonferonni-corrected critical alpha (.01). This analysis revealed that divided attention's impairment of navigational efficiency persisted throughout the majority of navigation trials. A marginal main effect of divided attention emerged for trial group 1, $F(1,23) = 4.8$, $p = .04$, $\eta_p^2 = .172$. This difference was significant in subsequent trial groups: 2, $F(1,23) = 13.7$, $p = .001$, $\eta_p^2 = .373$, 3, $F(1,23) = 9.48$, $p = .005$, $\eta_p^2 = .292$, and 4, $F(1,23) = 12.07$, $p =$

.002, $\eta_p^2 = .344$. Notably, the divided attention main effect disappeared in trial group 5.

Spatial Memory

For the following analyses, we used 2(Aid Presence) x 2(Divided Attention) repeated measures multivariate analyses of variance (MANOVAs). We used the same spatial memory measurements as in Experiment 1. Notably for the present experiment we excluded pointing response time as this measure neither reached significance in Experiment 1's analyses nor revealed informative patterns. The spatial memory measures included in the analysis were: landmark recall, canonical organization/accuracy, distance/angle accuracy, and pointing error. Table 5 presents means of the spatial memory measures.

The multivariate result indicated a significant main effect of aid presence, $F(6,18) = 2.82$, $p = .04$, $\eta_p^2 = .484$. Univariate tests revealed spatial memory impairment in the presence of navigational aid for landmark recall, $F(1,23) = 17.4$, $p < .001$, $\eta_p^2 = .431$, canonical organization, $F(1,23) = 10.72$, $p = .003$, $\eta_p^2 = .318$, pointing error, $F(1,23) = 7$, $p = .02$, $\eta_p^2 = .233$, and marginally for canonical accuracy, $F(1,23) = 4.09$, $p = .06$, $\eta_p^2 = .151$. Distance and angle accuracy means trended in the same direction.

The multivariate result also indicated an aid presence x divided attention interaction, $F(6,18) = 2.82$, $p = .04$, $\eta_p^2 = .484$. Univariate test suggested that the presence of navigational aid impaired spatial memory when attention was undivided but did not further impair memory when attention was divided. Univariate tests revealed this interaction for landmark recall, $F(1,23) = 7.18$, $p =$

.01, η_p^2 = .238, canonical organization, $F(1,23) = 9.1$, $p = .006$, η_p^2 = .283, and pointing error, $F(1,23) = 4.94$, $p = .04$, η_p^2 = .177. Figure 6 depicts the pattern of the interaction for canonical organization, which generalizes to the other measures.

We also looked more closely at the landmark recall task, examining the distance between sequentially recalled landmarks. These analyses permit inference of mental scanning during this task. We first calculated the distances between sequentially remembered landmarks (i.e. inter-landmark distances, ILDs) using the XY coordinates from the virtual environments and the distance formula. We removed 4 participants because they erroneously drew a sketch map during their first landmark recall task. This error obfuscated the order in which landmarks were recalled. We also removed one additional participant, who in one condition, remembered only two landmarks and thus yielded only one ILD. For the remaining 19 participants we averaged the ILDs to produce one ILD mean for each participant and condition. We submitted ILD means to a 2(Aid Presence) x 2(Divided Attention) repeated measures ANOVA which revealed a significant main effect of aid presence, $F(1,18) = 5.71$, $p = .03$, η_p^2 = .241. Overall, distances between sequentially remembered landmarks were greater in the presence of navigational aid. Neither a main effect of divided attention nor a 2-way interaction was observed.

Individual Differences

Working Memory Capacity and Divided Attention. We next examined how individual differences influenced navigation performance and spatial memory. We first investigated how WMC interacted with divided attention. WMC reflects the capacity to maintain information in the face of interference (Engle, 2001). Therefore WMC may be protective against spatial memory impairment caused by divided attention. To explore this possibility we linearly regressed participants' WMC scores with difference scores of the spatial memory measures that were significant and marginal in the previous MANOVA. We created attention difference scores for the aid present and aid absent conditions. For aid present the difference score subtracted the Aid in Noise condition from the Clear Aid and for aid absent subtracted Words in Noise from Control. These difference scores reflect the impairment of divided attention. Linearly regressing WMC with the difference scores revealed a stable pattern across several measures. The aid present regressions yielded no relationships. This is unsurprising given that divided attention did not further impair spatial memory when attention was divided relative to undivided (see Table 5 and Figure 6). However aid absent results suggested WMC is protective of divided attention's spatial memory impairment. For clarity, we have divided the measures into accuracy measures, where greater values indicate better memory, and error measures, where lower values indicate better memory. As shown in Table 6, for canonical accuracy, distance accuracy (marginal), and angle accuracy, accuracy measures' difference scores decreased linearly with increasing WMC. Similarly for the error measures, pointing error (marginal) difference scores increased linearly with increasing WMC. Because pointing error measures error (i.e. lower scores indicate better performance), and not accuracy, the interpretation remains the same. Overall these results suggest that, when the aid is absent, high WMC led to less spatial memory impairment when attention was divided. Figure 7 presents Z-normalized difference scores for the accuracy and error measures as a function of WMC.

Gender Effects. We examined gender effects by including gender as a between-participants factor in our previous analyses.

Navigation Performance. For navigational efficiency (i.e. path efficiency), a gender x trial group interaction emerged, $F_{GG}(2.64,58.16) = 4.13$, $p = .01$, $\eta_p^2 = .158$. As shown in Figure 8, males' navigational efficiency (collapsed across experimental groups) was low initially but increased rapidly as trial groups progressed, reaching a stable and high level of efficiency relatively early. In contrast, females' navigational efficiency was higher initially but increased more gradually in a linear fashion.

Spatial Memory. For the spatial memory MANOVA, we only included measures that emerged significant in the previous analysis (landmark recall, canonical organization, pointing error). Neither a main effect of gender nor an aid presence x divided attention x gender interaction emerged.

Gender Effects Relationship to Other Individual Difference Measures. The observed navigational efficiency gender effects may have stemmed from other individual differences. In the present sample, males reported greater video game frequency ($M = 2.4$ hours per week) than females (1.2), $t(16.1) = 3.33$, $p = .004$, higher sense of direction (SBSODS, $M_{males} = 5.1$ vs. $M_{females} = 3.8$), $t(22) = 3.19$, $p = .004$, and global self-confidence ($FRS_{\text{Global Self Confidence}}$, $M_{males} = 4.9$,

$M_{females}$ = 3.9), $t(22) = 2.21$, $p = .04$. We next examined if these individual differences contributed to the observed gender effects.

To accomplish this we first conducted three linear regressions with each measure as the dependent variable and gender as the independent variable, saving the unstandardized residuals. The residuals conceptually represent the measures devoid of the contribution of gender. We then ran bivariate correlations on the residuals. The observed correlations (see Table 7) suggested that the measures may reflect similar abilities and justified creating a composite score. To accomplish this, we conducted a principle components analysis (PCA) on the residuals. Three factors emerged from the PCA (see Table 8). Only one factor possessed an eigenvalue ($\lambda = 1.936$) that exceeded 1 and was therefore selected. Based on its loadings (see Table 9), this factor appeared to reflect spatial ability and spatial self confidence. We then submitted this composite score as a covariate in the navigation performance analysis that yielded significant gender effects. These analyses revealed a composite score main effect for navigation performance, $F(1,22) = 5.49$, $p < .05$, $\eta_p^2 = .200$.

Discussion

Experiment 1's results demonstrated spatial memory impairment through navigational aid use and suggested divided attention may underlie impairment. An open question remains: to what extent does divided attention contribute to this impairment? Experiment 2 addresses this question by examining how divided attention and aid presence contribute to navigational aids' spatial memory impairments. The two factors impacted navigational efficiency and spatial memory differently. Contrary to our prediction and the findings of Experiment 1, aid presence did not increase navigational efficiency. The source of this surprising finding is evident in Figure 5. When attention is undivided (as in Experiment 1) navigational aid improves navigational efficiency, as expected. In contrast, when attention is divided we see the opposite, with navigational aid appearing to impair efficiency. In addition to removing the predicted aid presence main effect, this pattern also revealed a main effect of divided attention. Divided attention systematically decreased navigational efficiency as trials progressed, an effect that persisted until the last navigation trial group. This finding suggests that dividing attention during navigation impairs efficiency but that as navigation progresses the impairment can be overcome.

Turning to the spatial memory results, some of our predictions were supported while others were not. Consistent with our predictions, we observed a main effect of aid presence. As in Experiment 1, the presence of a navigational aid impaired spatial memory, a finding that was evident across multiple measures. Taken together with Experiment 1, the present results point to a stable pattern of spatial memory impairment from navigational aid use. However, contrary to our predictions we did not observe a main effect of divided attention, despite divided attention's observed impact on navigational efficiency.

More telling, we observed a spatial memory interaction between aid presence and divided attention. At the outset, we offered conditional hypotheses concerning this interaction. If navigational aids impair spatial memory through distinct mechanisms, either distinct from or in concert with divided attention, we would expect additional impairment when attention was divided. Such additional impairment would reflect a distinct mechanism that acts to impair spatial memory together with the divided attention engendered by the aid. If, however, navigational aids impair spatial memory solely through divided attention mechanisms, then we would expect impairment from navigational aids in undivided but not divided attention contexts. Our results support the divided attention account. Aid presence influenced spatial memory differently when attention was divided vs. undivided. When attention was undivided, aid presence greatly impaired spatial memory (as in Experiment 1). But when attention was divided, aid presence did not further impair spatial memory. Further, aid presence alone and divided attention alone impaired spatial memory to the same extent. These findings suggest navigational aids impair spatial memory primarily through dividing attention.

Navigation

Our navigational efficiency results share similarities and notable differences with Experiment 1. First, as before, in all conditions navigational efficiency improved as navigation trials progressed, indicating that participants built adequate spatial mental representations of the environments during navigation. However, in contrast to Experiment 1, aid presence did not increase navigational efficiency. The lack of an aid presence main effect appears to be driven by the Aid in Noise condition (aid present, divided attention), which impaired navigational efficiency the most (see Figure 5). The design of the divided attention condition may explain this peculiar finding. We set the relative noise volume level in the divided attention task to yield chance performance for recognition of the embedded navigational commands. Further, the pilot testing was conducted without an additional task to consume attentional resources, such as navigation. Nevertheless, the hit rate for detecting reversed aid commands was 58% in the Aid in Noise condition. This suggests that participants allocated a large portion of their attention to deciphering and comprehending the aid commands during navigation. Critically, it appears that the Aid in Noise condition (*M* hit rate = .58) divided attention more than the Words in Noise condition (*M* hit rate = .33). Rather than assist navigation, it appears that the *aid* in noise had an additive effect on divided attention during navigation, undermining the aid's ability to assist navigation.

Spatial Memory

The main finding concerning spatial memory suggests that navigational aids impair spatial memory primarily through diving attention. Aid presence impaired spatial memory. However, when attention was divided the presence of an aid did not further impair memory. This finding suggests that the divided attention task caused participants to reach a "threshold" of impairment such that aid presence did not further impair spatial memory. This finding is consistent with previous research demonstrating that dividing attention leads to encoding failure and subsequently impoverished memory (Anderson et al., 1998; Baddeley et al., 1984; Chrastil & Warren, 2012; Craik et al., 1996; Murdock, 1965).

An open question remains: how might divided attention engendered by navigational aids impact one's spatial mental representation of the navigated environment? Our landmark recall data offer a possible suggestion. Participants presumably mentally scanned their mental representation of the navigated environment when recalling landmarks. Aid presence led to increased distances between sequentially remembered landmarks. This result suggests in the absence of navigational aid, participants were more likely to remember adjacent landmarks, mentally simulating a path through the environment to facilitate landmark recall. In contrast, when aid was present, participants were less likely to utilize this path approach. Instead they appeared to mentally scan by "jumping" to and from non-adjacent landmarks. Ishikawa and Montello's (2006) findings on spatial memory development suggest that survey knowledge rapidly develops over the course of navigation but that integration of separately learned places into a singular survey representation takes more time. Taking this view, "jumping" mental scanning as a result of navigational aid use appears to reflect impaired integration of spatial knowledge into a singular representation. We note that this inference remains speculative as we did not collect open-ended participant report of landmark recall strategies.

Individual Differences

Working Memory Capacity (WMC) and Divided Attention.

The evidence thus far suggests navigational aids impair spatial memory by dividing attention. If this is the case, we would expect WMC to be protective against this impairment because WMC reflects the capacity to maintain information in the face of interference. This advantaged ability would translate into better spatial mental representation encoding when attention is divided. This observation was borne out in the data. As depicted in Figure 7, the participants' spatial memory impairment afforded by divided attention decreased as WMC increased. This finding suggests high WMC navigators are less susceptible to the memory detriments of navigational aid use.

Gender Effects. Gender effects commonly occur in spatial cognition experiments (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Montello, Lovelace, Golledge, & Self, 1999; Silverman & Eals, 1992) and the present experiment is no exception. We observed gender effects for navigation performance. Females' navigational efficiency was higher than males' initially but increased more gradually than males as navigation progressed. When gender effects occur an important question is what factors provoke their occurrence. In this case, differential spatial ability and spatial self confidence appeared to underlie the navigation performance gender effect. After combining the individual difference measures (with the contribution of gender removed) into a spatial ability / spatial self-confidence composite score, we found this score motivated the navigation gender effect. This is consistent with previous research demonstrating that women report higher levels of spatial anxiety than males (Lawton, 1994; Lawton & Kallai, 2002). Concerning spatial memory, previous research has demonstrated better performance for males on pointing tasks (Waller, 2000) and on memory tests of environmental knowledge gained from direct experience (Montello et al., 1999). However, we did not observe spatial memory gender effects that have been noted previously. Thus, though navigation unfolded differently for males and females, differential navigation behavior did not appear to affect the development of spatial mental representations.

Strengths and Limitations

To our knowledge Experiment 2 is the first to examine the role of divided attention as it relates to navigational aids and spatial memory using a factorial design. Previous research has found that navigational aids impair spatial memory (Burnett & Lee, 2005) and some researchers have suggested that divided attention may underlie impairments (Fenech et al., 2010). However, Fenech et al. (2010) made an a priori prediction that navigational aids cause inattentional blindness and then interpreted observed impairments as supporting their prediction. In contrast, Experiment 2 directly manipulated divided attention using carefully designed divided attention tasks. By including divided attention as an independent variable in the experimental design, Experiment 2 determined both the role of divided attention in spatial memory impairment and its interaction with the presence of a navigational aid. Further, in Experiment 2, our sample represented genders equally (in contrast to Experiment 1) and we collected additional individual difference measures that included working memory capacity. These measures gave additional support to our divided attention interpretation.

However, limitations exist in the present experiment. One apparent limitation is our divided attention tasks. We crafted these tasks through careful pilot-testing. Nevertheless, as we touched on previously, our navigation performance data suggest that the Aid in Noise condition divided attention to a greater extent than the Words in Noise condition. This likely occurred because the information embedded in the Aid in Noise condition was task-relevant. Rather than monitoring word phrases that had no consequences for navigation, participants in the Aid in Noise condition listened for embedded aid commands that assist navigation. It appears that despite these embedded commands being helpful for navigation, allocating additional attention away from navigation to decipher the commands negatively impacted navigational efficiency more than expected. Nevertheless, this limitation did not appear to carry over to the spatial memory findings. As is evident in Table 5, the Aid in Noise condition neither yielded the lowest spatial memory scores nor supported a divided attention main effect.

In addition, we modified our filler task midway through data collection. At the experiment outset, participants completed a 5-minute filler task between conditions in which they donned a head-mounted display and tracked a moving virtual ball. However, this task caused motion sickness in several participants resulting in attrition. We switched the filler task to a 5-minute break halfway through data collection. We acknowledge that modifying experimental procedures during data collection is never advised. However, it appeared that tasks served the same purpose and did not systematically bias the data in any way.

General Discussion

The present pair of experiments explored the cognitive impact of navigational aid use, specifically how navigational aids impair spatial memory during navigation. Much research supports the existence of this impairment (Aporta & Higgs, 2005; Bakdash, et al., 2010, Bakdash, 2010; Burnett & Lee, 2005; Fenech et al., 2010; Girardin & Blat, 2010; Ishikawa et al., 2008; Leshed et al., 2008; Parush et al., 2007; Péruch & Wilson, 2004) but disagrees on its source. Both real-world consumer GPS and the simulated navigational aids used in previous studies often provide navigation commands in verbal format and route perspective. However, previous experiments have neither considered verbal working memory (VWM) interference nor spatial-perspective switching costs (Brunyé & Taylor, 2008; Shelton & McNamara, 2004) as potential explanations for observed memory impairments. Experiment 1 incorporated these considerations by contrasting a verbal and tonal aid and using mixed spatial perspective commands. Experiment 1 demonstrated that neither VWM interference nor spatial-perspective switching underlay spatial memory impairments. Rather, the results pointed to a general divided attention effect. This finding motivated Experiment 2.

Using a factorial design, Experiment 2's conditions crossed aid presence and divided attention to determine divided attention's role in impairment. Experiment 2's findings suggest divided attention underlies navigational aids' spatial memory impairment. That is, navigational aids impair memory for navigated environments by distracting navigators during environmental encoding, leading to an impoverished spatial mental representation (Anderson et al., 1998; Baddeley et al., 1984; Chrastil & Warren, 2012; Craik et al., 1996; Murdock, 1965). In addition, individual differences supported this interpretation. Working memory capacity (WMC) reflects the ability to maintain information in working memory in the face of interference. Experiment 2 demonstrated that high-WMC participants were less susceptible to memory impairment from divided attention.

Future Directions

The present experiments demonstrated that *auditory* navigational aids impair spatial memory. However, real-world navigational aids, such as consumer GPS, often possess *visual* components as well. Determining the cognitive impact of visual design features of navigational aids is an important goal for future research. Human-computer interaction studies have revealed that navigational aids using a graphical interface divert more attention from the road during driving than voice-only interfaces but users nevertheless prefer interfaces with graphical components (Jensen, Skov, & Thiruravichandran, 2010; Kun et al., 2009). Other human factors research has evaluated the aesthetics and usability of graphical interface features (Lavie & Oron-Gilad, 2013; Schreiber, 2009). Some recent research has directly examined the cognitive impact of graphical interface design (Li, Zhu, Zhang, Wu, & Zhang, 2012; Schmid, Richter, & Peters, 2010; Wu, Zhang, & Zhang, 2009) but more research is needed. In addition to visual design considerations, altering the presentation modality of navigational aids may reduce spatial memory impairment and divided attention. Medenica, Kun, Paek, & Palinko (2011) demonstrated that presenting navigational aid via an augmented reality (AR) interface reduces divided attention during a simulated driving task. In light of this finding, future research should examine if AR navigational aid interfaces reduce spatial memory impairment.

Final Comments

People increasingly rely on navigational aids, such as consumer GPS, during navigation. With the advent of smartphones many now have a GPS on hand at all times and dependence on these technologies is rising (uShip, 2012). This is a problematic trend given that navigational aids impair spatial memory (Burnett & Lee, 2005). In light of this usage context, cognitive research must examine and uncover the mechanisms by which navigational aids impair spatial memory. The present set of experiments took a first step in this direction but more research is needed. People will continue to use devices, such as GPS, for their convenience regardless of their cognitive impact. Determining the cognitive impact of these devices and using research findings to inform their design will provide products that improve quality of life without cognitive expense.

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Table 1. Experiment 1: Mean (and SE) Path Efficiency by Aid Type and Trial Group.

	Trial Group									
	G1		G2		G3		G4		G5	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Verbal	.719	.033	.707	.025	.721	.026	.755	.024	.720	.021
Tonal	.616	.040	.648	.027	.756	.023	.822	.019	.747	.021
Control	.530	.047	.637	.032	.714	.027	.720	.026	.731	.029

Table 2. Experiment 1: Means and SEs for spatial memory measures.

Task	Measure	Aid Type	*M*	*SE*
Virtual Pointing	Point Error	Verbal	44.74	3.03
		Tonal	45.10	2.75
		Control	33.79	2.44
	Response Time	Verbal	11283.33	552.52
		Tonal	10664.76	447.52
		Control	10963.52	630.38
Landmark Recall	n of Landmarks	Verbal	10.75	0.31
		Tonal	11.33	0.40
		Control	12.89	0.35
Map Drawing	Canonical Organization	Verbal	0.47	0.03
		Tonal	0.49	0.04
		Control	0.64	0.04
	Canonical Accuracy	Verbal	0.81	0.02
		Tonal	0.78	0.02
		Control	0.85	0.01
	Distance Accuracy	Verbal	0.86	0.01
		Tonal	0.85	0.01
		Control	0.87	0.01
	Angle Accuracy	Verbal	0.80	0.02
		Tonal	0.79	0.02
		Control	0.84	0.01

Table 3. Experiment 2: Nonsense phrases and their matched navigational commands.

Nonsense Phrases	Navigational Commands
Respect	Forward
Applause to the thing	Slightly to the right
To the thing	To the right
Stupid and stubborn to the thing	Behind and slightly to the right
Moment	Behind
Stupid and annoying to the mind	Behind and slightly to the right
To the show	To the left
Annoying to the mind	Slightly to the left
Now walking past	One hundred feet
Any walking past	Two hundred feet
Years walking past	Three hundred feet
Each walking past	Four hundred feet
Both walking past	Five hundred feet
Dog walking past	Six hundred feet
Buddy walking past	Seven hundred feet
Horse walking past	Eight hundred feet

Table 4. Experiment 2: Mean (and SE) Path Efficiency by Divided Attention, Aid Presence, and Trial Group.

		Trial Group									
Divided Attention	Aid Presence	G1		G2		G3		G4		G5	
		M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Divided	Present	.453	.059	.565	.046	.582	.047	.624	.036	.665	.035
	Absent	.509	.069	.594	.043	.595	.037	.602	.026	.710	.024
Undivided	Present	.673	.063	.698	.033	.737	.035	.731	.030	.689	.031
	Absent	.579	.052	.661	.043	.698	.033	.702	.026	.714	.029

Table 5. Experiment 2: Means and SEs for spatial memory measures.

Task	Measure	Divided Attention	Aid Presence	*M*	*SE*
Virtual Pointing	Pointing Error	Divided	Present	43.89	3.77
			Absent	43.04	3.41
		Undivided	Present	49.00	4.23
			Absent	38.06	4.01
Landmark Recall	n of Landmarks	Divided	Present	11.21	.42
			Absent	12.33	.47
		Undivided	Present	10.25	.61
			Absent	13.33	.38
Map Drawing	Canonical Organization	Divided	Present	.51	.05
			Absent	.56	.05
		Undivided	Present	.47	.05
			Absent	.69	.04
	Canonical Accuracy	Divided	Present	.79	.02
			Absent	.83	.02
		Undivided	Present	.82	.02
			Absent	.85	.02
	Distance Accuracy	Divided	Present	.86	.01
			Absent	.87	.01
		Undivided	Present	.86	.01
			Absent	.88	.01
	Angle Accuracy	Divided	Present	.79	.03
			Absent	.83	.02
		Undivided	Present	.82	.02
			Absent	.85	.02

Table 6. Linear regression statistics for WMC (independent) and divided attention difference scores (dependent) for spatial memory measures.

Measure Type	Measure	Aid Presence	R^2	*F* for change in R^2	*B*	β	*t*
Accuracy Measure	Canonical Accuracy	Present	0	0	0	-0.001	-0.004
		Absent	0.19	5.16*	-0.006	-0.436	.2.27*
	Distance Accuracy	Present	0.03	0.63	0.001	0.167	0.795
		Absent	0.14	3.64^{+}	-0.002	-0.377	-1.91^{+}
	Angle Accuracy	Present	0.003	0.07	0.001	0.056	0.26
		Absent	0.17	4.62*	-0.005	-0.417	-2.15*
Error Measure	Pointing Error	Present	0.06	1.35	0.307	0.24	1.16
		Absent	0.13	3.39^{+}	0.592	0.365	1.84^{+}

* $p \leq .05$, $^{+}$ $.05 > p \leq .1$

Table 7. Correlations between unstandardized residuals of individual difference measures that differed between genders.

Measure	SBSODS	$FRS_{Global\ Self\ Confidence}$
Video Game Frequency	-0.218	-0.160
SBSODS	1	0.859**

* $p < .01$, ** $p < .001$

Table 8. Eigenvalues and % variance explained for principle components analysis.

	Initial Eigenvalues	
Component	Total	% of Variance
1	1.936	64.521
2	0.925	30.849
3	0.139	4.630

Table 9. Factor loadings for spatial ability / spatial self confidence factor.

Measure	Component 1
Video Game Frequency	-0.383
SBSODS	0.952
$FRS_{Global\ Self\ Confidence}$	0.940

Figure 1. Ground level view of environment 1.

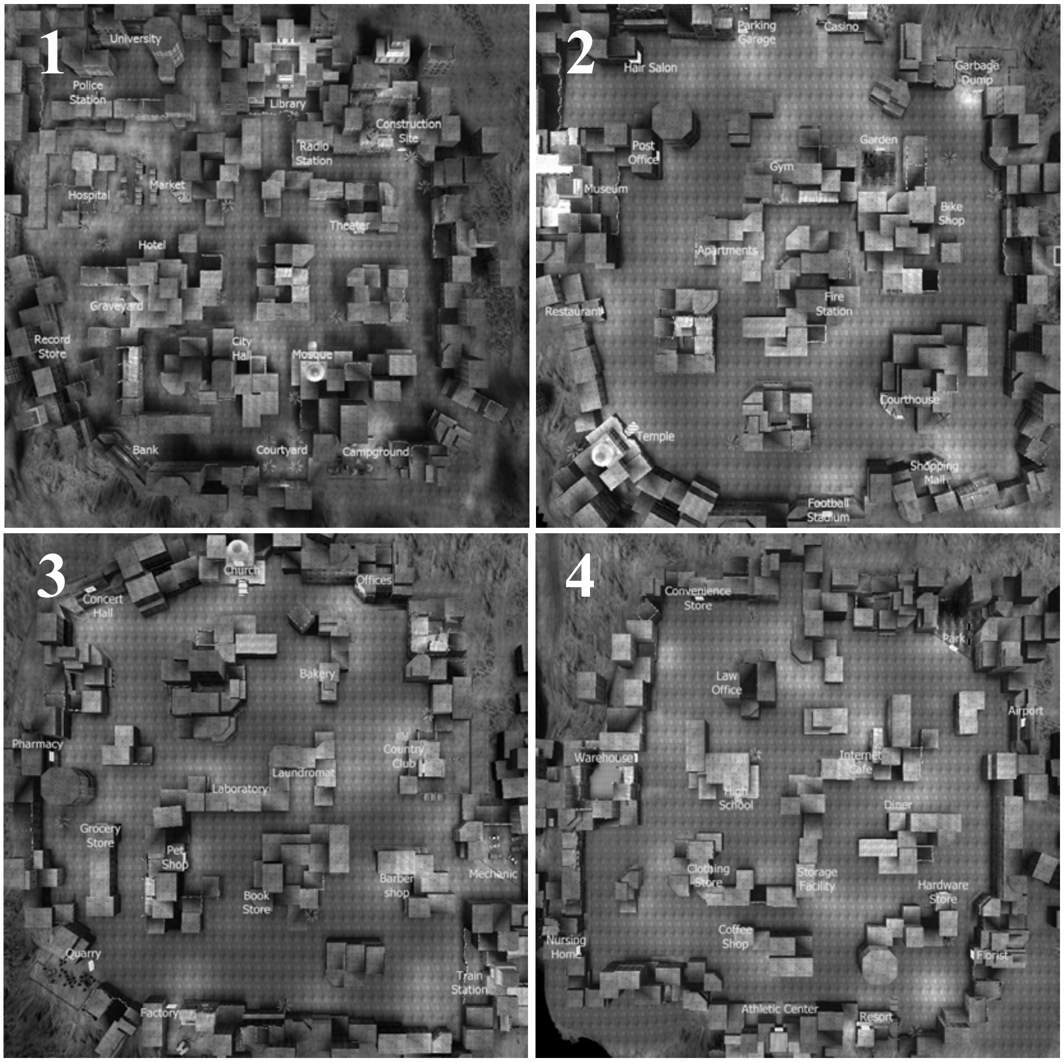

Figure 2. Overhead views of the four virtual environments (VEs). VEs 1 - 3 were used in Experiment 1. All VEs were used in Experiment 2.

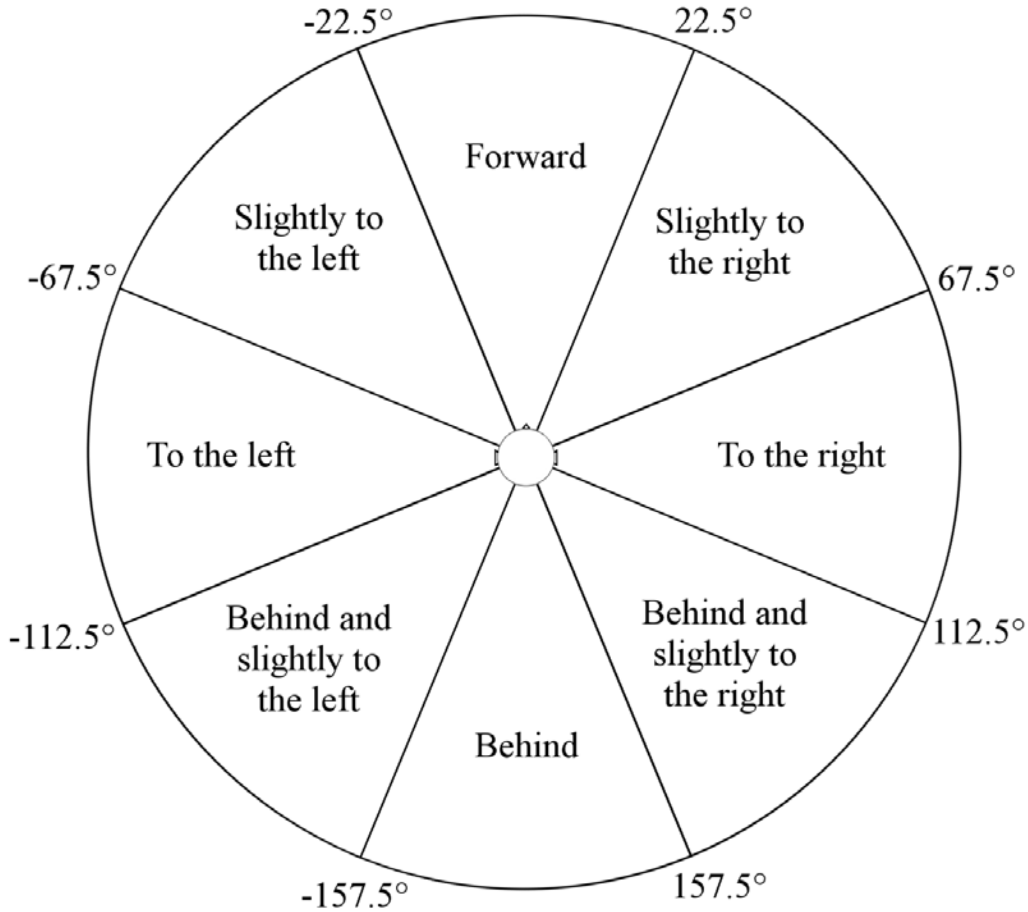

Figure 3. The 8 azimuths used in the Experiment 1 and 2's navigational aids

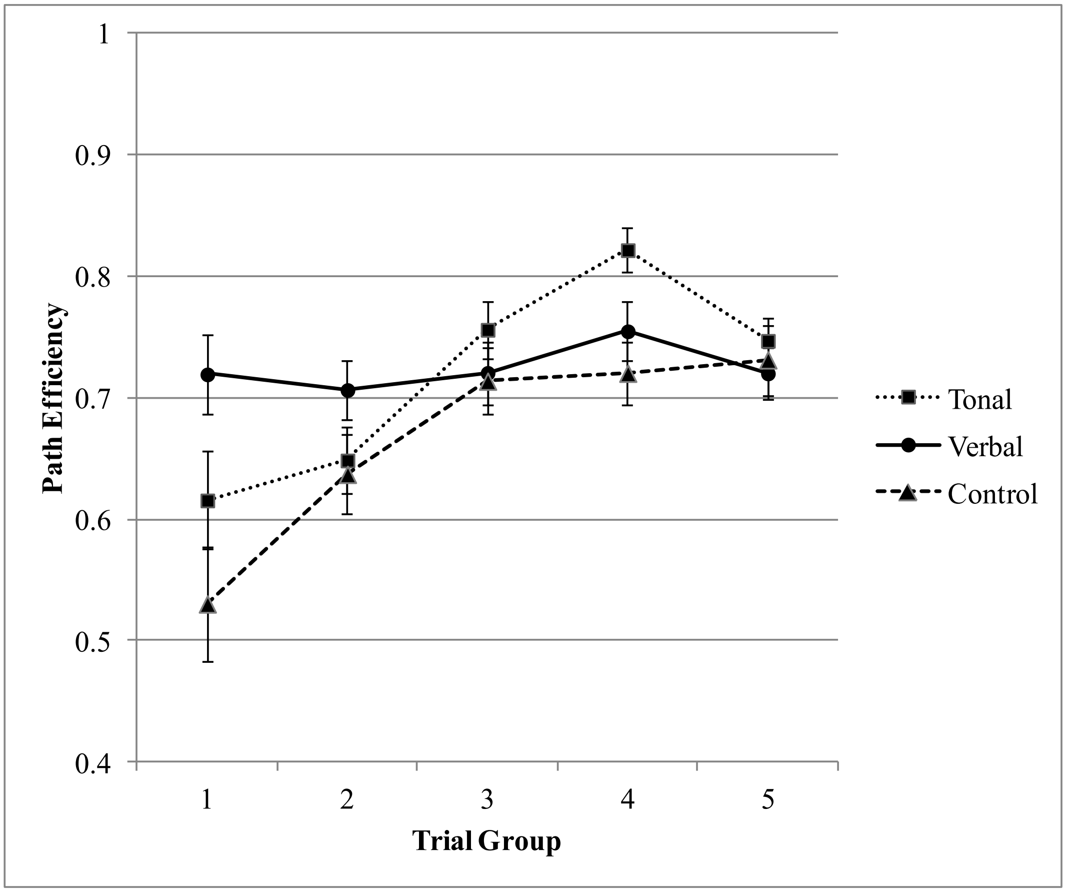

Figure 4. Experiment 1: Mean path efficiency as a function of aid type and trial group. Error bars show SE.

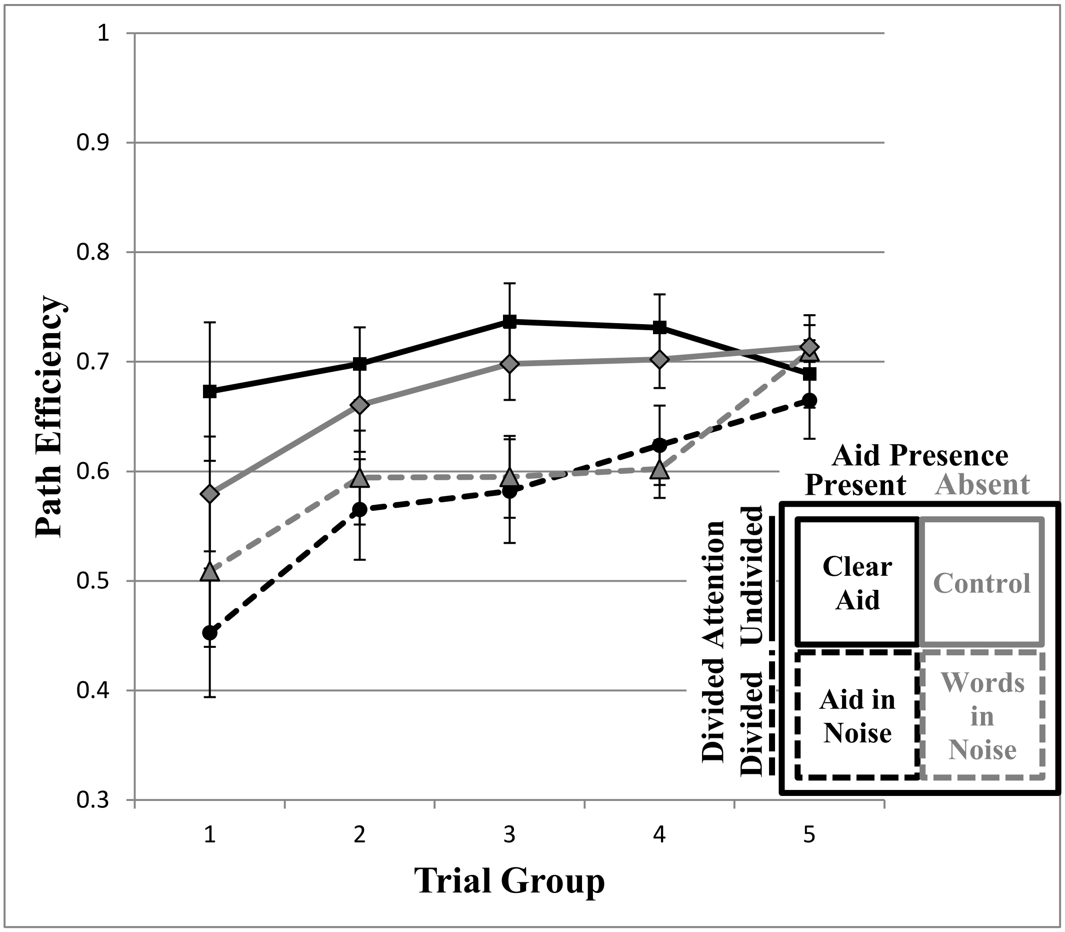

Figure 5. Experiment 2: Mean path efficiency as a function of divided attention, aid presence, and trial group. Error bars show SE.

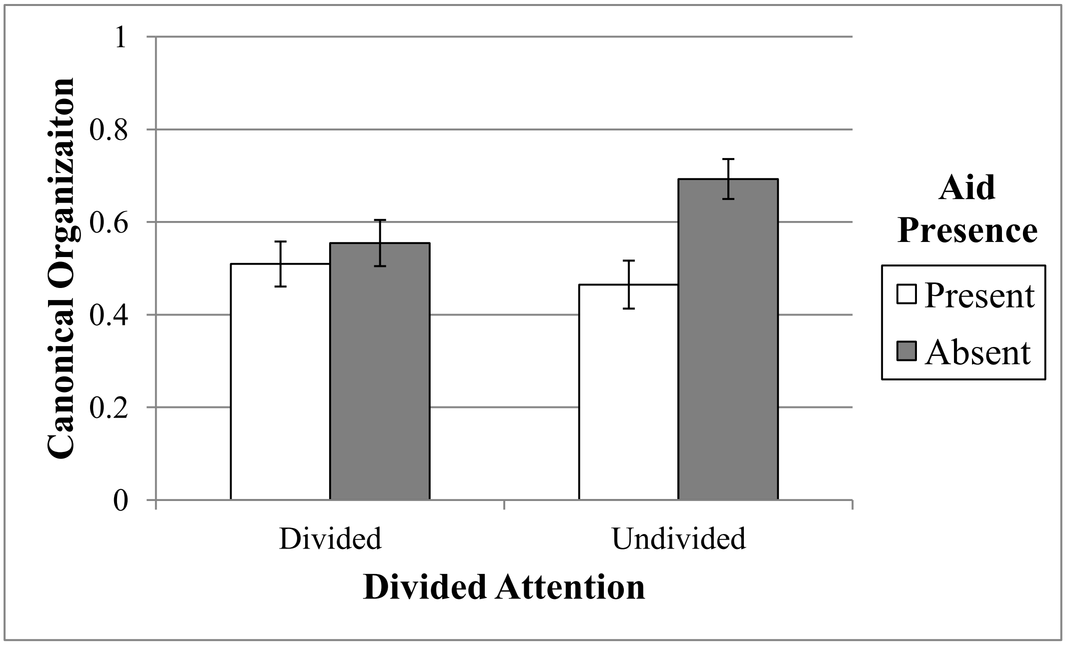

Figure 6. Experiment 2: Mean canonical organization as a function of aid presence and divided attention. Error bars show SE.

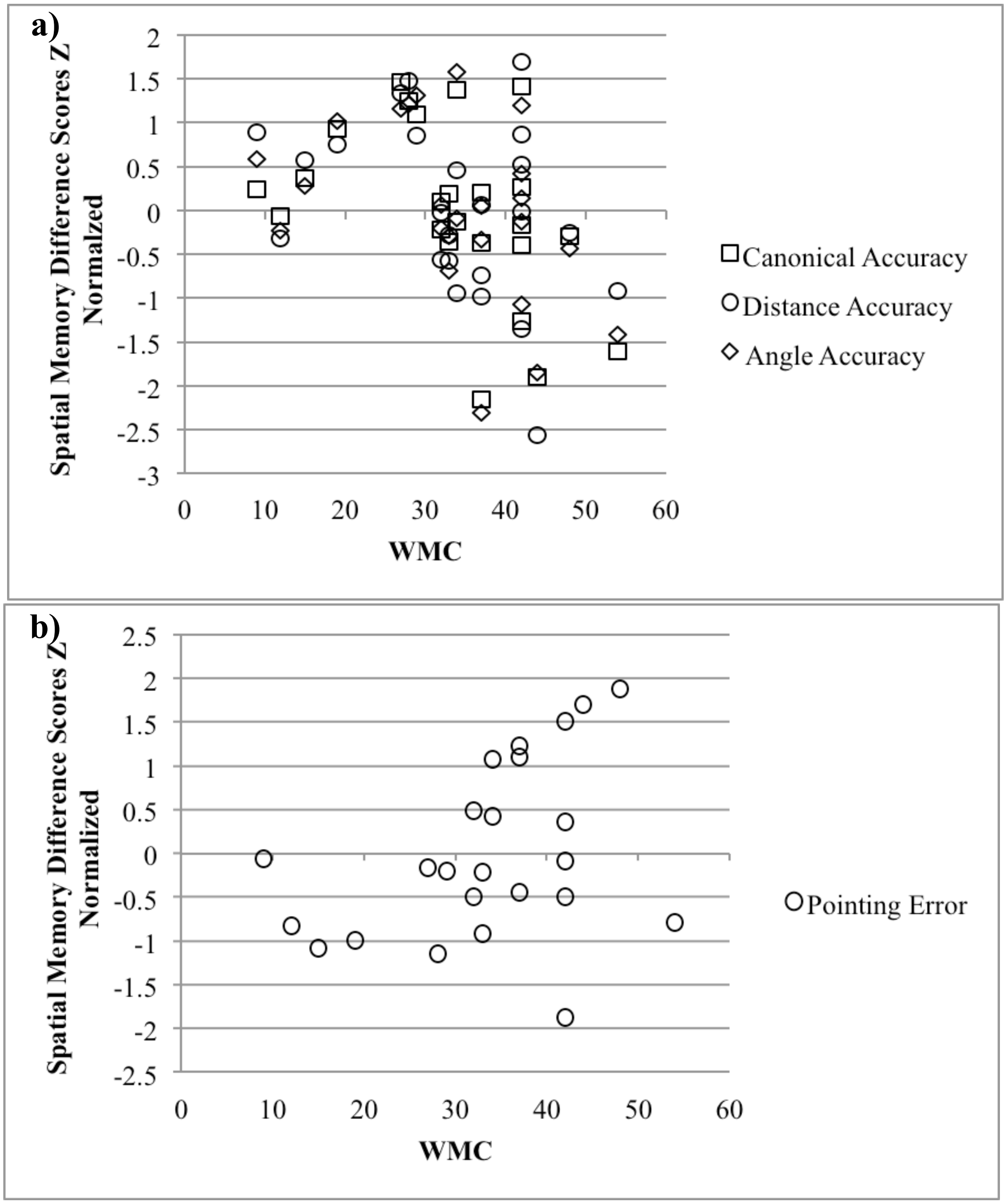

Figure 7. Z-normalized spatial memory difference scores (aid absent, divided attention - undivided) as function of WMC for accuracy (a) and error (b) measures. These difference scores can be conceptualized as the impairment afforded by divided attention. Note that for the accuracy measures positive values represent increased impairment and for the error measures negative values represent increased impairment.

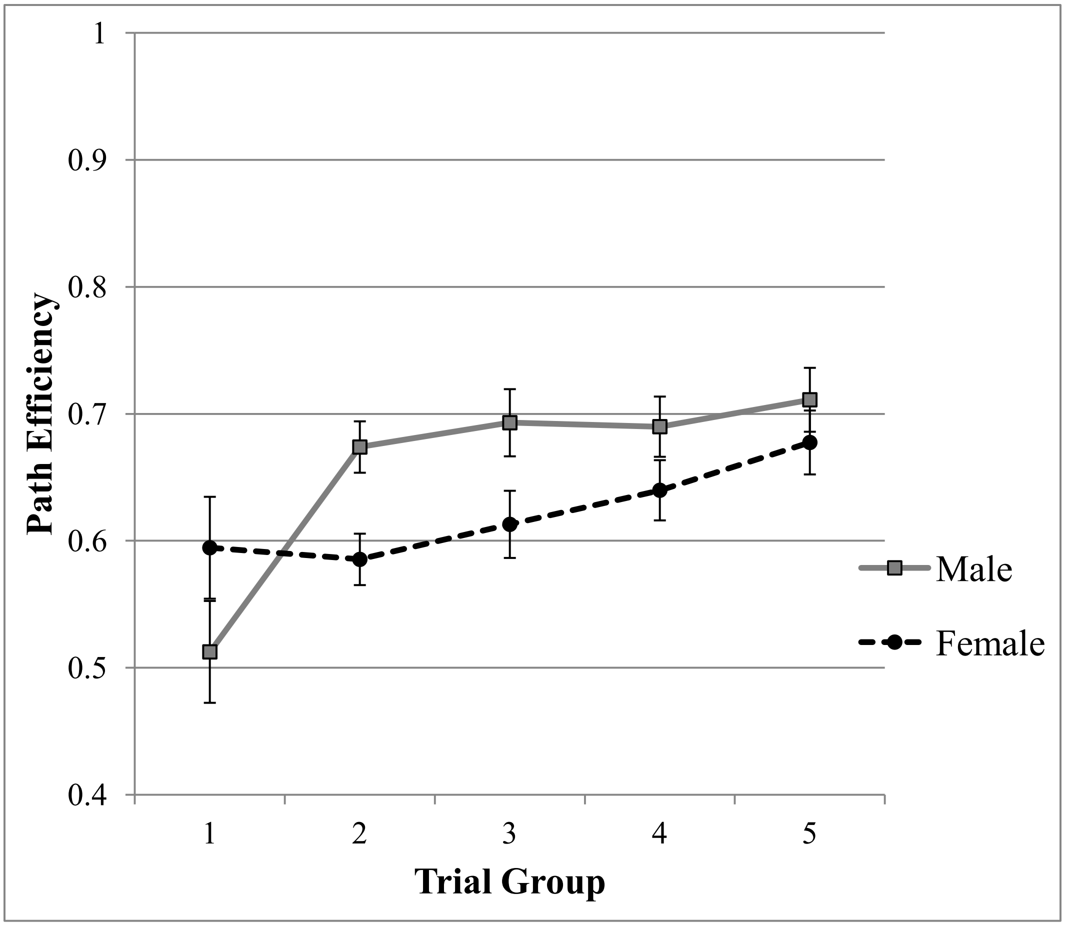

Figure 8. Experiment 2: Mean path efficiency as a function of gender and trial group. Error bars show SE.

Appendix A.

For experiment 1, custom software first compared participants' head width to database entries using the error formula detailed by Zotkin et al. (2004) producing a head width error term (HWE) for each of the HRTF database subjects. Using the same formula an error term for each pinna parameter was also calculated. Prior to averaging these terms into an overall pinnae error score (PE), error terms exceeding 2 standard deviations from the mean were removed for each database subject. Once both error terms were calculated they were scale equalized by dividing each term by the sum of the error terms for all database subjects. The software then equally weighted and summed the resulting scores to produce a final error term. The HRTF database subject with the lowest error term (and thus the corresponding binaural recordings) was selected as the best match for the participant.

Appendix B.

Environment 1

Starting Location: Bank

1. City Hall
2. Hotel
3. Campground
4. Library
5. Hospital
6. Mosque
7. Radio Station
8. Police Station
9. Record Store
10. Theater

Environment 2

Starting Location: Bike Shop

1. Gym
2. Shopping Mall
3. Garbage Dump
4. Fire Station
5. Apartments
6. Courthouse
7. Post Office
8. Garden
9. Temple
10. Casino

Environment 3

Starting Location: Concert Hall

1. Bakery
2. Laundromat
3. Train Station
4. Mechanic
5. Pet Shop
6. Offices
7. Laboratory
8. Factory
9. Grocery Store
10. Country Club

Environment 4

Starting Location: Florist

1. Diner
2. Clothing Store
3. Convenience Store
4. Internet Cafe
5. Hardware Store
6. Coffee Shop
7. Airport
8. Athletic Center
9. High School
10. Nursing Home

Appendix C.

$$\text{Distance Accuracy} = 1 - \frac{\sum|\text{Observed Distance} - \text{Actual Distance}|}{\binom{\text{n of observed landmarks}}{2}}$$

$$\text{Angle Accuracy} = 1 - \frac{\frac{\sum|\text{Observed Angle}-\text{Actual Angle}|}{\binom{\text{n of observed landmarks}}{2}}}{180}$$