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Abstract: Research has demonstrated navigational aids impair spatial memory, but has not considered important spatial cognitive concepts. For example, impairment may stem from spatial perspective switches between route-based aids and survey-based memory assessments. Further, the verbal format of aid instructions may selectively interfere with verbal working memory (VWM). To address these potential explanations, participants navigated desktop virtual environments in a goal-directed manner. In each within-participants condition, participants either navigated with a verbal or tonal aid that presented mixed spatial perspective instructions or without aid. Both aids yielded slight navigational advantages and steep spatial memory costs despite their mixed perspective instructions. The equivalent impairment between information formats suggests navigational aids impair spatial memory by dividing attention rather than selective interference of VWM.

Keywords: spatial memory, navigational aids, virtual reality/virtual environments, navigation

1. 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.

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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). Although 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 study addresses this need by examining the influence of navigational aids on both virtual navigation performance and spatial memory.

1.1. 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 postnavigation 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 impairment 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, 2010; Bakdash, Linkenauger, & Proffitt, 2008), 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. We detail some of these considerations below.

1.2. Spatial Perspectives

One such spatial cognitive concept 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 maplike, 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.

1.3. 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, 2002; Baddeley & Hitch, 1974; Baddeley & Logie, 1999), 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.

1.4. The Present Study

The present study 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. Last, by virtue of its design, the present study 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, the present study 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. The present study 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 nav-
igation 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, the present study 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, the present study’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.

The present study 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; Gunther, Kazman, & MacGregor, 2004; Holland, Morse, & Gedenryd, 2002; Klatzky, Marston, Giudice, Golledge, & Loomis, 2006; Lokki & Grohn, 2005; Loomis, Golledge, & Klatzky, 1998; Simpson et al., 2005). Further, given its nonverbal 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. The present study 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.

In the present experiment, 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.

2. METHODS

2.1. Participants and Design

Thirty-six male Tufts University undergraduates (age \( M = 19.5 \)) partici-
pated 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 mini-
mize order effects, we fully counterbalanced aid type and environ-
ment type across participants; this process resulted in 36 unique aid and environ-
ment combinations \((3! \times 3! = 36)\), one per participant.

2.2. Materials

2.2.1. 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 1.76 m and avatar movement speed was 8.8 m/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.

2.3. Navigational Aids

2.3.1. 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.”).
Figure 2. Overhead views of the three virtual environments.

Figure 3. The 8 azimuths used in the present study’s navigational aids.
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. Finally, it relayed this information via a verbal recording presented through closed-ear headphones every 5 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.

2.3.2. 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. The present study 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 semipersonalize 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 semipersonalized 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.

2.4. 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.

2.5. Procedure

2.5.1. 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.

2.6. Experimental Sessions

During an experimental session, participants first studied an overhead view of the VE for 1 minute. They then followed onscreen instructions (e.g., “go to the bank”) to navigate between predefined, fixed-order sets of landmarks. Appendix B presents the ordered landmark sets for each VE. Participants completed ten navigation trials in their assigned navigational aid condition. Following navigation, participants completed landmark recall, listing all landmarks they could remember in 5 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 piece of 8.5” × 11” paper. Participants completed three test sessions, one for each aid condition, separated by at least four hours to prevent carryover effects.

2.7. Coding

2.7.1. 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).

2.8. Virtual Pointing Analysis Software

Custom software analyzed participants’ virtual pointing data. The critical measure reported here is point 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.

2.9. 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 \( \binom{16}{2} = 120 \) 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.

Although 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: $-180^\circ$–$+180^\circ$) 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.

2.10. 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 that scale all interlandmark 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 interlandmark 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 study’s 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.

3. RESULTS

3.1. 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.
3.1.1. 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) × 5(Trial Group: 1, 2, 3, 4, 5) repeated measures ANOVA. There was a main effect of Aid Type, \( F(2, 70) = 7.21, p = .001, \eta^2_p = .171 \). Follow-up contrasts revealed that navigators in both the verbal aid, \( F(1, 35) = 10.03, p = .003, \eta^2_p = .223 \), and the tonal aid conditions, \( F(1, 35) = 9.68, p = .004, \eta^2_p = .217 \), demonstrated higher path efficiency than control. Analysis also revealed a main effect of Trial Group, \( F(4, 140) = 15.08, p < .001, \eta^2_p = .301 \). Follow up contrasts revealed higher path efficiency in trial groups 3, \( F(1, 35) = 18.43, p < .001, \eta^2_p = .345 \), 4, \( F(1, 35) = 31.36, p < .001, \eta^2_p = .473 \), and 5, \( F(1, 35) = 21.8, p < .001, \eta^2_p = .384 \), relative to group 1. The main effects were qualified by an Aid Type by Trial Group interaction, \( F(8, 280) = 2.56, p < .05, \eta^2_p = .068 \) (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) on each trial group. Analysis revealed a main effect of aid type in trial group 1, \( F(2, 70) = 12.92, p < .001, \eta^2_p = .144 \). As shown in Figure 4 and Table 1, during the first trial, navigators in the verbal aid condition demonstrated higher path efficiency than control, \( F(1, 35) = 10.87, p < .01, \eta^2_p = .237 \). In all other trial groups, no significant differences emerged.

3.1.2. 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, \( F(14, 22) = 3.26, p < .01, \eta^2_p = .674 \). Univariate tests showed differences by aid condition for pointing error, \( F(2, 70) = 10.77, p < .001, \eta^2_p = .235 \), landmark recall, \( F(2, 70) = 13.84, p < .001, \eta^2_p = .283 \), canonical organization, \( F(2, 70) = 12.67, p < .001, \eta^2_p = .266 \), canonical accuracy, \( F(2, 70) = 4.26, p < .05, \eta^2_p = .109 \), and angle accuracy, \( F(2, 70) = 3.45, p < .05, \eta^2_p = .09 \). 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).

Table 1. Mean (and SE) path efficiency by aid type and trial group

<table>
<thead>
<tr>
<th>Trial Group</th>
<th>G1 M</th>
<th>G1 SE</th>
<th>G2 M</th>
<th>G2 SE</th>
<th>G3 M</th>
<th>G3 SE</th>
<th>G4 M</th>
<th>G4 SE</th>
<th>G5 M</th>
<th>G5 SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal</td>
<td>.719</td>
<td>.033</td>
<td>.707</td>
<td>.025</td>
<td>.721</td>
<td>.026</td>
<td>.755</td>
<td>.024</td>
<td>.720</td>
<td>.021</td>
</tr>
<tr>
<td>Tonal</td>
<td>.616</td>
<td>.040</td>
<td>.648</td>
<td>.027</td>
<td>.756</td>
<td>.023</td>
<td>.822</td>
<td>.019</td>
<td>.747</td>
<td>.021</td>
</tr>
<tr>
<td>Control</td>
<td>.530</td>
<td>.047</td>
<td>.637</td>
<td>.032</td>
<td>.714</td>
<td>.027</td>
<td>.720</td>
<td>.026</td>
<td>.731</td>
<td>.029</td>
</tr>
</tbody>
</table>

**Figure 4.** Mean path efficiency as a function of aid type and trial group. Error bars show SE.
Table 2. Means and SEs for spatial memory measures

<table>
<thead>
<tr>
<th>Task</th>
<th>Measure</th>
<th>Aid type</th>
<th>M</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual Pointing</td>
<td>Point Error</td>
<td>Verbal</td>
<td>44.74</td>
<td>3.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tonal</td>
<td>45.00</td>
<td>2.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>33.79</td>
<td>2.44</td>
</tr>
<tr>
<td></td>
<td>Response Time</td>
<td>Verbal</td>
<td>11,283.33</td>
<td>552.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tonal</td>
<td>10,664.76</td>
<td>447.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>10,963.52</td>
<td>630.38</td>
</tr>
<tr>
<td>Landmark Recall</td>
<td>Number of Landmarks</td>
<td>Verbal</td>
<td>10.75</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tonal</td>
<td>11.33</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>12.89</td>
<td>0.35</td>
</tr>
<tr>
<td>Canonical Organization</td>
<td>Canonical Accuracy</td>
<td>Verbal</td>
<td>0.47</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tonal</td>
<td>0.49</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>0.64</td>
<td>0.04</td>
</tr>
<tr>
<td>Map Drawing</td>
<td>Distance Accuracy</td>
<td>Verbal</td>
<td>0.86</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tonal</td>
<td>0.85</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>0.87</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Angle Accuracy</td>
<td>Verbal</td>
<td>0.80</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tonal</td>
<td>0.79</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>0.84</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The MANOVA revealed no memory differences between the three environments, $F(14, 56) = 0.66$, $p > .1$.

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

4. DISCUSSION

The present study 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 navigation 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.

4.1. 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 our experimental 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 article.

4.2. 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, 2010; Bakdash et al., 2008). 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. The present study’s design sheds light on these arguments in the following ways.

First, the present study’s navigational aids did not completely eliminate the need for spatial decision making during navigation. Recall that the present 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 present study’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, the present study extends findings implicating attention in navigational aids. In using localized binaural audio the present study’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.

4.3. Strengths and Limitations

To our knowledge, the present study is the first to consider and control for spatial perspective in the context of navigational aids and their influence on spatial memory. Although previous studies reinforced a route perspective during learning, but tested memory with survey perspective tasks, the present experiment 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. Finally, 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 present study’s desktop VEs required no self-locomotion to navigate as other more immersive VE systems 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 the present study’s desktop VEs may partially explain the lack of a strong relationship between individual difference measures and navigation and spatial memory data.
Second, to provide functionally equivalent prior environmental knowledge between aid conditions, participants first briefly studied an overhead view of the environment prior to navigating it. Although 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 the present study’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.

Last, 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.

4.4. Future Directions

In extending previous findings, the present study suggests further research questions. The present study’s navigational aid 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, our 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. Forthcoming research by our group will address this need by comparing spatial memory after navigation with an aid compared to a divided attention task. Further, though our 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, our 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.

4.5. Implications and Conclusions

Given increasing navigational aid use, the present findings have real-world implications. While our findings further support detrimental effects of navigational aids on spatial memory (Burnett & Lee, 2005), they also demonstrate a limitation of aids for navigation. In the present study, control participants’ navigational efficiency matched aided efficiency relatively early in navigation. Thus, in somewhat familiar environments, navigational aids provide limited assistance. This is an important consideration given how frequently people use navigational aids in familiar environments. Persons in important roles, such as emergency first-responders and military personnel, for whom efficient navigation and spatial memory is crucial, should weigh the spatial memory costs and limited navigational benefits before using navigational aids.

Consistent with previous research, the present study 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 VWM interference. Rather, they appear to arise from general divided attention. Our results extend previously proposed explanations of the underlying causes of observed spatial memory impairments. We emphasize the need for continued research on the cognitive impact of navigational aids and careful examination of contributing factors to their navigation benefits and memory costs.
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REFERENCES


learn where they are going. *Human Factors and Ergonomics Society Annual Meeting Proceedings, 52*(27), 2117–2121.


APPENDIX A

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), we first removed error terms exceeding 2 standard deviations from the mean 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

APPENDIX C

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

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

\text{Angle Accuracy} = 1 - \frac{\sum |\text{Observed Angle} - \text{Actual Angle}|}{180}