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Cognitive Load of Navigating Without Vision When Guided by Virtual Sound Versus Spatial Language

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A vibrotactile *N*-back task was used to generate cognitive load while participants were guided along virtual paths without vision. As participants stepped in place, they moved along a virtual path of linear segments. Information was provided en route about the direction of the next turning point, by spatial language ("left," "right," or "straight") or virtual sound (i.e., the perceived azimuth of the sound indicated the target direction). The authors hypothesized that virtual sound, being processed at direct perceptual levels, would have lower load than even simple language commands, which require cognitive mediation. As predicted, whereas the guidance modes did not differ significantly in the no-load condition, participants showed shorter distance traveled and less time to complete a path when performing the *N*-back task while navigating with virtual sound as guidance. Virtual sound also produced better *N*-back performance than spatial language. By indicating the superiority of virtual sound for guidance when cognitive load is present, as is characteristic of everyday navigation, these results have implications for guidance systems for the visually impaired and others.

Keywords: blind, navigation, perception, virtual sound, cognitive load

People accomplish the feat of updating self-position and orientation by two basic mechanisms (Gallistel, 1990). One is piloting, which relies on encoding of environmental features for use as homing beacons or for computation of distance and angle (e.g., by triangulation). Relevant features for piloting can be physical objects, terrain changes, or components of paths, for example. The other updating mechanism is path integration, the process of sensing self-motion and using the sensed data to compute displacement and change in orientation with respect to a reference location, such as the origin of travel (Loomis, Klatzky, Golledge, & Philbeck, 1999).

People with visual impairments are at an obvious disadvantage when it comes to finding their way in the environment by piloting, which requires that they perceive environmental features beyond their reach. The sighted traveler can access areas of space with a single view and can cover substantial areas with multiple views over the brief period of time needed to move the eyes or head. Access to environmental features is far more limited for people without vision. Although environmental sensing from other modalities can be used to apprehend distal locations and support homing, these compensatory senses provide far less information and precision compared with vision (Thinus-Blanc & Gaunet, 1997). Distal environmental features can be apprehended through audition, olfaction, and thermal cues (Golledge, 1991; Porteous, 1985; Strelow, 1985). Although audition can be effective for judging the distance and direction of distal environmental features (Blauert, 1997), the olfactory and thermal senses are much less informative (see British Columbia Ministry of Education, 2001). Olfactory sources are localized with almost no precision, and whereas thermal information, such as sunlight through a window, can provide some amount of orientation information, it is transient and imprecise. To assess tangible but silent features, blind travelers must use touch, a proximal sense. Touch, particularly with an extension like a cane, is useful for obstacle monitoring and avoidance as well as detection of surface material (e.g., grass vs. concrete), but it does not support the ability to pilot in an extensive spatial environment.

Blind travelers, as a result, are at a profound disadvantage for independent travel. They have difficulty preplanning routes in new territory, recovering from unexpected detours, or maintaining heading (Espinosa et al., 1998; Passini, Delisle, Langlois, & Proulx, 1988). Despite these impediments, many blind people seek independent travel and show considerable success at it. They may use path integration, along with auditory or haptic cues, to walk without guidance, particularly in a regular layout such as a city grid.

Increasingly, technology has offered aids for the blind traveler (as reviewed in Giudice & Legge, in press; Loomis, Golledge, Klatzky, & Marston, in press). Obstacle-avoidance devices have

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been available for decades on the basis of sonar, for example (Kay, 2000; for reviews of early work, see Brabyn, 1985; Farmer, 1980). The utility of most of these mobility devices has been questioned, however, and the research assessing their value has been equivocal (Dodds, Clark-Carter, & Howarth, 1984; LaGrow, 1999).

Many outdoor urban environments now offer assistive devices such as sound cues at intersections and information postings that can be monitored with special receivers. The Talking Signs system consists of transmitters situated in the environment that emit infrared signals encoding speech information; these signals activate a handheld device whenever the user's hand points toward one of the infrared transmitters, and the user then hears the encoded utterance (Bentzen & Mitchell, 1995; Crandall, Gerrey, & Alden, 1993). These approaches require considerable investment by the community. A less costly alternative (currently as little as $600 but costing $5,500 or more for an advanced global positioning system [GPS] with a fully functional personal digital assistant designed for the blind) is to provide the blind traveler with a technology that tracks his or her position in space, relates the current positional data to a map, and displays route instructions and, potentially, other relevant information about the local surround. Such a system was conceived of by Loomis (1985). A prototype was developed at the University of California, Santa Barbara in 1993 and named the personal guidance system by Golledge. Subsequent versions have since been used for research. Others have embraced similar ideas and realized them in various forms for research and commercial purposes. In 2005, there were three commercial GPS devices that were accessible for people with visual impairments or blindness, including StreetTalk from Freedom Scientific (St. Petersburg, FL), Trekker from HumanWare (Christchurch, New Zealand), and the BrailleNote GPS from Sendero Group (Davis, CA; see evaluations by Denham, Leventhal, & McComas, 2004; NFB Access Technology Staff, 2006).

A unique feature of the University of California, Santa Barbara system is its use of virtual or spatialized sound to convey the location of features in the environment. Virtual sound makes use of various distance and direction cues, particularly binaural cues for spatial hearing, which are simulated by specialized hardware and software. When virtual sound signals are displayed by stereo earphones, the listener experiences sounds coming from different directions and distances in the environment, although accurate distance perception has proved difficult to achieve (Zahorik, 2002).

By virtue of simulating the primary cues for auditory spatial perception, virtual sound provides a direct perceptual avenue to the encoding of a source location (Begault, 1994; Carlile, 1996). It can be used both to inform a traveler about locations in the environment and to provide a homing cue to guide travel (Loomis, Hebert, & Cicinelli, 1990). It is the guidance function that we focus on in the present research, although we have examined location learning in previous work (Loomis, Golledge, & Klatzky, 1998). Specifically, virtual sound provides an instantaneous correction signal, in the form of perceived azimuth. If a traveler is walking to an audible landmark, any deviation from a direct route will be signaled by the perception of its source as coming from an angle other than straight ahead.

An alternative to virtual sound for corrective information is spatial language. Travelers can be told that a target location is to the right, 60° to the right, or at 2 o'clock, for example. In our previous work, reviewed below, we have compared various versions of virtual sound-based guidance to spatial language-based correction as well as other forms. As will be described, we have found that simple verbal corrections can be effective in allowing travelers without vision to find their way along paths.

Our group has performed a number of experiments evaluating the display interface with respect to route guidance. In the first of these experiments, Loomis et al. (1998) evaluated the personal guidance system with the virtual sound display, in comparison with speech-based displays, as users walked paths about 70 m in length. The speech-based displays gave correction in the form of verbal direction ("left," "right") or direction and degrees (e.g., "left 80"). The virtual display led to the shortest travel time and was preferred by participants (mean rating 4.4 on a 1- to 5-point scale vs. 4.0 for speech-based correction). However, the time advantage was largely visible at the slow update rate, every 5 s (average completion time of approximately 180 s for virtual sound vs. 250 s for speech). Speech yielded very similar results to virtual sound when updating occurred every 1.5 s.

In the second study on route guidance, we compared virtual sound with a "haptic pointer interface," which informed the user when he or she was pointing within 10° of the direction to the next waypoint (Loomis, Marston, Golledge, & Klatzky, 2005). The displays varied in whether they used speech or tones and, for the pointer interface, whether it measured orientation with the hand or body. All displays proved highly successful at guiding users over 50-m paths. Travel time was fastest, and user preference strongest, for the virtual sound display with a speech signal that gave current distance to the next waypoint. (When that display was compared with the one that used the pointer interface with speech feedback, i.e., said "straight" if the user was within 10° of target, and otherwise "left" or "right" to indicate the direction of error, $d = 0.84$ for time and $d = 1.08$ for preference rating.)

Our third study (Marston, Loomis, Klatzky, Golledge, & Smith, 2006) compared virtual sound with the haptic pointer interface on paths that lay along streets or within parks. When queried by the user with a push-button, the virtual sound interface emitted a rapid series of beeps that appeared to come from the direction of the next waypoint. The pointer interface, when queried, emitted beeps when the user's hand pointed within 10° of the direction to the next waypoint. Although the virtual sound was rated easier to use ($d = 2.20$), the devices showed no significant difference in traveled distance ($d = 0.23$) or number of queries to the system ($d = 0.20$), and virtual sound produced only a marginal advantage in completion time ($d = 0.49$).

In short, an extensive body of work reviewed above has found some advantages for virtual sound over other forms of interface in nonvisual navigation tasks. Still, correction in the form of spatial language has proven to effectively guide navigators over paths. This is somewhat surprising given that language does not constitute a direct perceptual channel.

Our previous work has not, however, assessed the processing cost of the different forms of guidance. More generally, the perceptual–cognitive load of navigation without vision has not been extensively studied. Existing research does point to the involvement of limited-capacity processes in navigation tasks. In an early study, Lindberg and Gärling (1982) tested people's ability to learn the locations of six reference points along a path that they walked, with or without a concurrent backwards-counting task.

The counting disrupted the ability to learn the layout. May and Klatzky (2000) examined the effects of cognitive load on spatial updating without vision. They found that when participants were asked to replicate the length of a single-leg path by returning to the origin, counting backward by threes led to no further error than did continuous verbalization of a nonsense sound. However, when the task became more complex—namely, completing a triangle after being guided along the first two legs—counting produced greater error than simply verbalizing.

In real-world navigation tasks, distractions are inevitable. Some, such as ambient noise, are perceptual. Others are cognitive. For example, travelers may have to hold directions in mind, engage in conversation, or seek landmarks. These tasks are demanding to cognitive capacity. In order to simulate the working memory load of these kinds of activities, the present study implemented an *N*-back task (e.g., Braver et al., 1997). In this task, a series of stimuli is presented, and the participant's task is to signal whenever a current stimulus matches one that was presented *N* steps back in the list. The value of *N* can be varied to assess individuals' level of performance or to set a level of dual-task competition. Advantages of the *N*-back task are that it has an objective accuracy criterion and that it measures capacity of cognitive processes, as opposed to perceptual limitations. Important for our research, the task can be implemented in a mode that does not involve vision, audition, or language (the last two being the forms of feedback in this research), namely, vibrotactile input.

The *N*-back task is a hallmark test of working memory load. Braver et al. (1997) found that areas of prefrontal cortex associated with reaction-time measures of working memory load were also those that showed progressively increasing activation as a function of *N*-back interval. Jonides et al. (1997) plotted brain activation as a function of *N*-back load for 11 different areas associated with verbal working memory and found that most showed monotonic increases in activation with load; in contrast, 6 areas thought a priori not to be involved in working memory failed even to show a significant effect of memory load. Cohen et al. (1997) further found evidence that the load-induced increases in activation reflected processing intensity and not merely time spent on the task.

Modality-specific versions of the task have been used to test for the existence of different forms of working memory. Specificity of its effects was demonstrated by Postle, D'Esposito, and Corkin (2005), who found that verbal distraction affected *N*-back performance with objects, whereas motion distraction had an impact on performance with object location. Ravizza, Behrmann, and Fiez (2005) found that a patient with a right parietal lesion, associated with deficits of spatial processing, was impaired in a spatial *N*-back task regardless of load, whereas a verbal *N*-back task was essentially unaffected.

We used the *N*-back task to assess the cognitive load of navigating with corrections from virtual sound versus spatial language. We hypothesized that virtual sound, being processed at direct perceptual levels, would have lower load during navigation than simple language commands, which require cognitive mediation. Accordingly, participants should show poorer navigation performance—in the form of longer distance traveled or greater time to complete a path—when performing the *N*-back task along with spatial language, even if spatial language does not differ significantly from virtual sound under no-load conditions. Evidence for this hypothesis comes from a variety of studies.

The efficacy of direct perceptual guidance for navigation has been demonstrated in experiments with vibrotactile stimulators, which cue desired direction by the location of a stimulus or the direction of a series of stimuli applied to the skin (Van Erp & Van Veen, 2004; Van Erp, Van Veen, Jansen, & Dobbins, 2005). Localized tactile stimulation has been offered as an aid in maintaining spatial orientation in the absence of gravity (Bhargava et al., 2005).

Auditory spatial cues have been shown to be highly effective in directing visual attention (Begault, 1993; Perrott, Sadralodabai, Saberi, & Strybel, 1991). As with the navigation studies described above, speech-based cues have also been found to be useful, in some cases being indistinguishable from spatial perceptual cues. In a study directly relevant to the present one, Ho and Spence (2005) compared spatial audition (a tone presented from the left or right) with equivalent verbalizations ("left" or "right") in a driver simulation task, in which drivers had to detect impending dangerous situations. They found an accuracy advantage for the direct spatial cues, which was offset, however, by faster reactions to the verbal cues. Three-dimensional sound has also been tested in aviation cockpit environments. Begault and Pittman (1996) found that the time to detect potentially colliding aircraft was faster when warnings used 3-D sound than when a map display accompanied by monaural alert was used. A similar effect was obtained by Oving, Veltmann, and Bronkhorst (2004). The latter study also directly compared directional information (e.g., "up") from 3-D sound and spatial language. The two cues were equally effective, and the combination of both together was approximately additive.

The relative load of processing spatial language was assessed in previous studies by ourselves and colleagues. We found that azimuths of an array of targets were learned more slowly from spatial language than directional sound (Klatzky, Lippa, Loomis, & Golledge, 2002) and also that targets learned from spatial language produced somewhat more systematic error ($d = 0.52$) and between-subjects variability in spatial updating without vision (Klatzky, Lippa, Loomis, & Golledge, 2003).

In the present study, the load of spatial language versus virtual auditory cues was directly assessed in the context of a virtual navigation task. Blindfolded participants attempted to travel on a simulated pathway, either in the absence of a competing task or when simultaneously monitoring a series of vibrations to the hand for repetitions (*N*-back task). Our principal interest was in comparing the effect of the competing task across spatial language versus virtual sound. The value of *N* was set to 1, which pretesting indicated was sufficient to compete effectively with the navigation task and which was quite difficult for some pilot participants. Because of the intensive equipment demands, which precluded physical movement, we simulated navigation by stepping in place, as shown in Figure 1. Each step moved the participant along a virtual path of linear segments. The participant's position in the virtual space was tracked, and he or she received information en route about the direction of the next turning point, or waypoint. In the spatial language condition, information was reduced to three simple, discriminable terms ("left," "right," "straight"), to minimize perceptual load. In the virtual sound condition, the perceived azimuth of the sound indicated the direction of the waypoint.

Figure 1. Apparatus for the navigation task: (A) push button, (B) body orientation sensor, (C) vibrator on finger, (D) head orientation sensor, (E) footstep sensor (also shown in inset).

Method

Participants

Sixteen students from the University of California, Santa Barbara, balanced equally by gender and ranging from 19 to 27 years old, were recruited through a participant pool and personal contact to participate in this experiment. All participants had normal sight and showed normal hearing abilities by demonstrating correct perception of the straight-ahead cue from the virtual sound condition.

Procedure

The participant wore a blindfold and walked in place along a simulated path, consisting of linear segments beginning and ending with waypoints. He or she faced a target waypoint, walked until it was reached and the next waypoint was announced, turned toward the next waypoint and walked in place, and so on until completing the path. Guidance information was delivered either by spatial language or by virtual spatialized sound. In the *N*-back condition, the participant also responded to the *N*-back task.

Eight different paths were stored in the computer database. Each path had six turning points, including both a left and right 90° turn and two left and two right 45° turns. There were thus seven legs to each path. Legs were of various lengths, but the total length of each path was a constant 70 steps long. For the initial two practice trials, participants used a single path. Subsequent trials used unique paths. The order of paths was randomly ordered for each participant.

In order to ensure a high standard of performance on the *N*-back test, from which departures due to competition could be measured, was first conducted a 1-min *N*-back test before any navigation task was performed. All participants were required to perform with at least 80% correct hits and fewer than 20% false positives. No one was eliminated by this criterion during prescreening.

The two guidance modes were experienced in succession, with the order counterbalanced across participants. In the virtual sound mode, a beeping sound was delivered every 0.5 s through stereo headphones with binaural cues so that the sound appeared to be coming from the direction of the next waypoint. The intensity of the virtual sound was inversely proportional to the square of the distance between simulated source and computed head position. The virtual sound was just audible at the farthest distances used and was loud, but not uncomfortable, when the source was within a few centimeters of the head. In the spatial language mode, directions were spoken monaurally to the user: "straight" if he or she was within 10° to either side of the target, and "left" or "right" to indicate the direction needed to correct if he or she was outside this zone. The verbal signal was given every 1 s.

Apparatus

Two computers (both ES100 by Gateway, Irvine, CA) were used, one controlling navigation and one delivering and monitoring the *N*-back task. Time-linked data from the two sources were then merged. For the navigation task, a custom-designed foot switch was attached to the dominant foot to count footsteps. It consisted of a momentary contact response switch mounted to a strip of aluminum and attached to the bottom of the foot with Velcro. When a step on that foot depressed the switch, the user advanced one unit forward in the virtual world in the direction the body was facing. (Foot dominance was determined by participant report or, if uncertain, was assumed to be on the same side as the dominant hand.)

A computer program written using Vizard software (WorldViz, Santa Barbara, CA; www.worldviz.com) generated a virtual world within which the eight different paths were navigated. An orientation sensor on the body enabled the computer to track a participant's current heading along the path and was used for language feedback. A similar orientation sensor on the head was used to determine the correct binaural cues for the virtual sound source. The orientation sensor for the head was an Intersense IS-300 (Bedford, MA), and the one on the body was an Intersense InertiaCube2 (Bedford, MA). Both are 3-degrees-of-freedom sensors, but we read only the yaw axis (i.e., rotation around the gravitational axis). Both use angular rate gyros, linear accelerometers, gravitometers, and magnetometers to determine orientation. The angular accuracy is 1.0° root-mean-square and angular resolution is 0.02° RMS. The update rate was approximately 60 Hz. Each was connected to the computer by a serial port.

Distance units used in the program were in terms of "steps," as defined by signals from the foot switch. If a target was positioned in virtual space to be 12 units from the participant's starting position, all participants would reach the target by taking 12 steps, if walking straight to it. When the participant moved within 2 steps of a target waypoint, the next waypoint in the series was activated until all were visited. A data file recorded the time and distance, along with *x*- and *y*-coordinates, once per second.

Headphones that covered the ears (Optimus Pro25; Radio Shack, Fort Worth, TX) were used to deliver the auditory information about the current waypoint relative to the participant's position. In the virtual sound condition, the current waypoint was simulated as a sound source at a location in the virtual world. Vizard was used to specify and update the waypoint locations relative to the user. DirectSound software by Microsoft (n.d.) was used to produce the virtual sound signals for the specified locations, and additional sound processing was provided by a Turtle Beach Santa Cruz (Voyetra Turtle Beach, Yonkers, NY) sound card.

For the *N*-back task, vibrators (Audiological Engineering, VBW32 Skin Transducer, Somerville, MA; 1 in. long × 0.73 in. wide × 0.42 in. thick [2.54 cm × 1.85 cm × 1.07 cm]) were mounted with Velcro on the tip of the participant's thumb, middle finger, and little finger. The *N*-back program, also created with Vizard, caused one of three vibrators to vibrate by playing a 290-Hz square wave WAV file on the computer and routing the audio signal from the sound card randomly to one of three vibrators (thus, the probability of a 1-back repeat was 0.33). The routing was done by an Advantech (Milpitas, CA) multi-input–output card connected to a custom-designed multiplexer, which sent the audio signal from the computer's sound card to the vibrator specified by a randomly generated series of the integers 1, 2, and 3. The time sequence was vibration on for 0.5 s and off for 1.0 s. Participants were instructed to depress a handheld custom-designed push-button whenever the same finger received two vibrotactile stimuli in a row. The button was attached to a momentary contact switch that was connected to the input–output card's digital input.

The *N*-back program monitored which vibrator was currently vibrating and also which vibrated on the previous interval. If a vibrator vibrated twice in a row and the participant pressed the push-button before the next vibration began, the program recorded a correct identification. During each interval, the program recorded whether the response was a correct identification, a correct rejection, a false alarm, or a miss. This information was used to present a message on the screen indicating the participant's accuracy rate, which was updated at every stimulus presentation and was saved to a data file at the conclusion of the experiment.

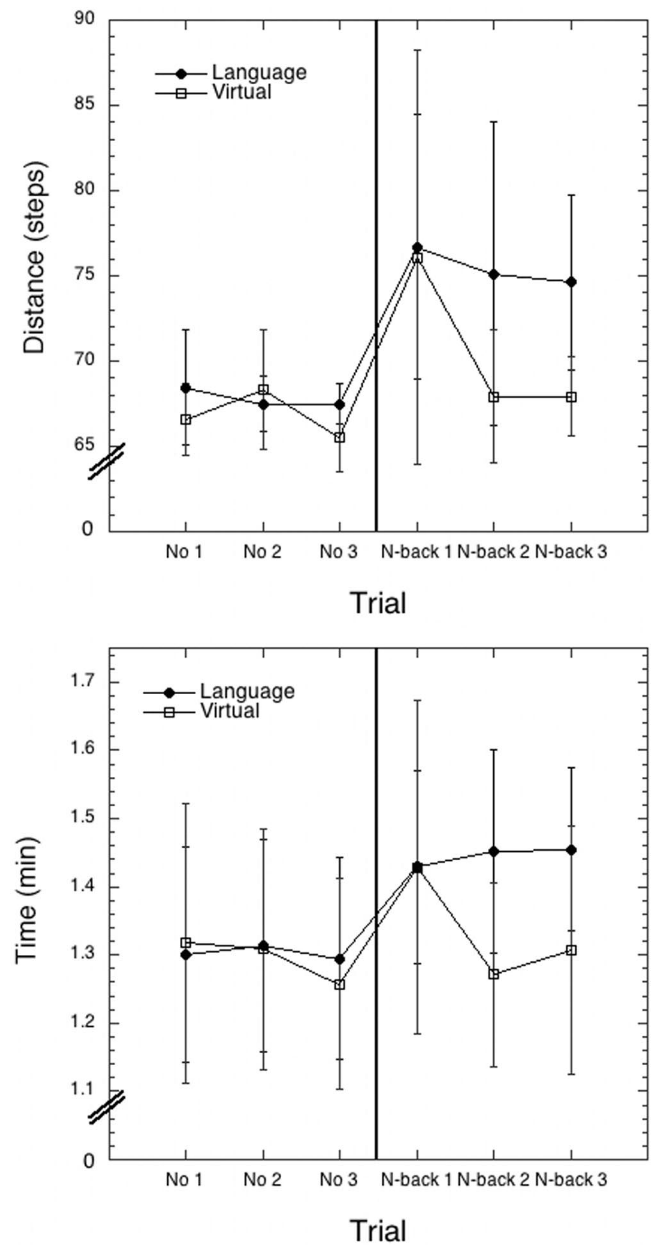

Figure 2. Distance (top) and time (bottom) for navigation in the six experimental trials, progressing from no-load to *N*-back, by guidance mode (spatial language vs. virtual sound). Error bars are the 95% confidence intervals.

Design

The design was completely within participants, with the order of the two guidance modes counterbalanced. The following sequence of events occurred within each guidance condition: (a) familiarization with guidance and vibration, (b) navigation with vibration but no *N*-back for three trials, (c) refresher training with *N*-back, and (d) navigation with *N*-back for three trials. The analyzed data were drawn from Phases b and d. We chose to consistently implement the no *N*-back version before the *N*-back, because we wanted the participants to have experience with guidance before adding the cognitive load. Pilot testing showed that three or more trials were often needed for navigation performance to stabilize. This design confounds the cognitive load variable with practice, which could lead to underestimating the effects of the load manipulation on unpracticed navigators.

To initially familiarize participants with the cues of the guidance system, we gave them a short practice path with a visible target, so that they could watch their progress on the computer monitor and relate it to the correction signals. Each depression of the foot switch caused them to move forward in the virtual world. By watching the monitor, participants were able to see the relationship between the input from the headphones to their movement through the environment and progress toward the target on the screen. The nature of the cues was also explained verbally. Participants were then blindfolded and performed two practice trials with navigation alone, where the research assistant was free to offer suggestions and discuss problems. At that point, the vibrators were put on the fingers of the dominant hand and the push-button was placed in the nondominant hand. The vibrators were run in a random fashion, but participants were not to use the push-button. A third practice trial was then performed without assistance to accustom the participant to the vibration. There then commenced three trials without the *N*-back task but with the random vibration. These were followed by an optional rest break.

Before beginning the next three trials, which used the *N*-back task concurrently with navigation, we reversed the hand placement of the push-button and vibrators, to avoid vibrotactile adaptation. Participants performed another 1-min trial with the *N*-back task alone. They were instructed to try to keep the same level of competence when subsequently attempting to perform *N*-back concurrently with the navigation task.

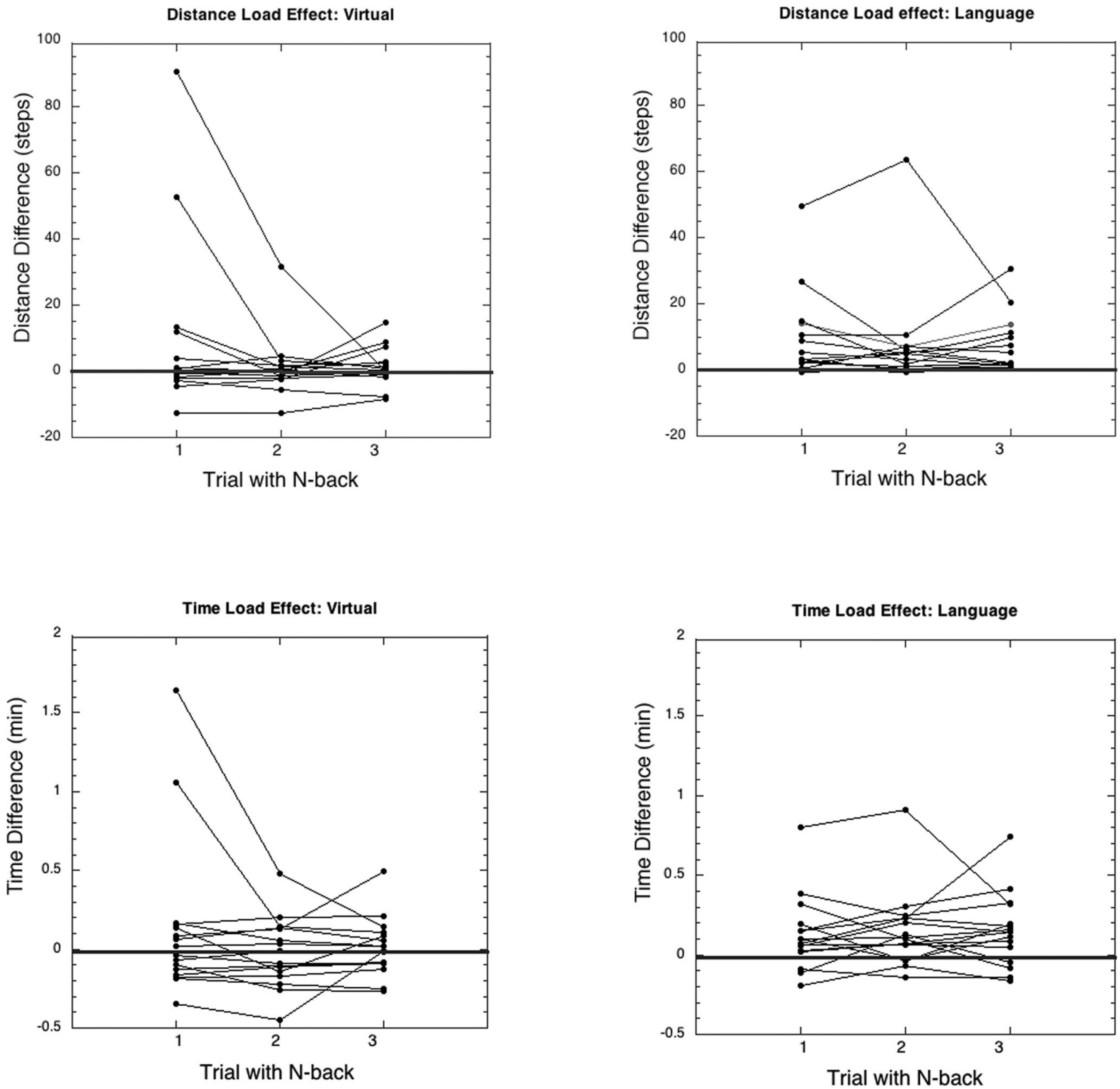

Figure 3. Effect of the *N*-back task over three successive trials, as measured by difference relative to the mean of three previous trials with no load, by guidance mode (virtual sound, spatial language). Top: Effect on distance. Bottom: Effect on time. Absence of an effect of the *N*-back task would lead to data lying on the zero bar, shown in boldface. Each line is an individual participant.

Participants then performed three navigation trials with concurrent *N*-back, followed by a required rest break. The entire procedure from practice to *N*-back was then repeated with the second guidance mode. At the end of the experiments, participants filled out a short questionnaire that asked, among other questions, which of the two navigation conditions was easiest to perform when also concentrating on the vibratory task.

Results

The independent variables of principal interest were guidance mode (virtual, language) and cognitive load (presence–absence of *N*-back). Our hypothesis predicted an interaction between these variables in measures of travel time and/or distance.

Recall that in our design, after familiarization, participants performed three trials without *N*-back, followed by three with *N*-back, in each guidance condition. This followed practice with the basic navigation task and a trial combining it with vibration (but not *N*-back).

Figure 2 shows the mean distance and time over these six trials. The figure indicates that given the familiarization procedure, performance had reached steady state by the first experimental trial without *N*-back. We had intended the first trial with *N*-back to be practice, and in keeping with this assumption, it is apparent that the transition to *N*-back impaired performance. In the case of the virtual sound, however, this was due to 2 participants who had particular difficulties with the transition but recovered on the next trial. This can be seen in Figure 3, which shows each participant's performance in the three *N*-back trials, relative to the mean of the three preceding trials without load (i.e., the data shown are the participant's *N*-back time and distance by trial, minus his or her mean for the three preceding no-load trials). If there was no effect of the *N*-back task, the difference relative to preceding trials without load should be zero. Table 1 shows the means and standard deviations by trial for each guidance mode and measure. Averages for the virtual sound condition are near zero after the first trial with *N*-back, whereas the trend in the spatial language condition is to increase on the first *N*-back trial relative to preceding trials but not to recover fully on successive *N*-back trials (the 95% confidence interval excludes zero for all trials with language but includes zero for all trials with virtual sound). There were, however, individual differences in performance; some participants had little difficulty with *N*-back under each guidance mode.

The evaluation of load effects focused on the mean data from the last two trials for each guidance mode, in each load condition. In general, participants performed very well on these trials. Paths in three out of the four conditions were completed on average with fewer than 70 steps (i.e., the actual path distance), the savings being attributable to cutting corners. Average time was less than 1.5 min per path. Sample trajectories are shown in Figure 4, selected to show examples of very accurate tracking and tracking with some error.

The mean d' in the *N*-back task for the last two trials was 2.15 for language and 2.48 for virtual sound. A t test comparing d' between the two guidance modes showed a significant difference, $t(15) = 2.08$, $p < .05$ (one-tailed), $d = 0.35$. This finding suggests that the demands of navigation in the language condition led to less attention to the competing *N*-back task, which might lead to underestimating the disadvantage for language relative to virtual sound.

Nonetheless, analyses indicate that any lapse in attention to *N*-back was not sufficient to mask the cognitive load of navigating by spatial language. The analyses of variance on mean distance and time for the last two trials per condition, by guidance mode and load, are reported in Tables 2 and 3. Both show the anticipated results: The two guidance modes were not significantly different in the absence of cognitive load: For distance, $t(15) = 0.43$, $d = 0.14$; for time, $t(15) = 0.56$, $d = 0.06$ (note, however, that low power

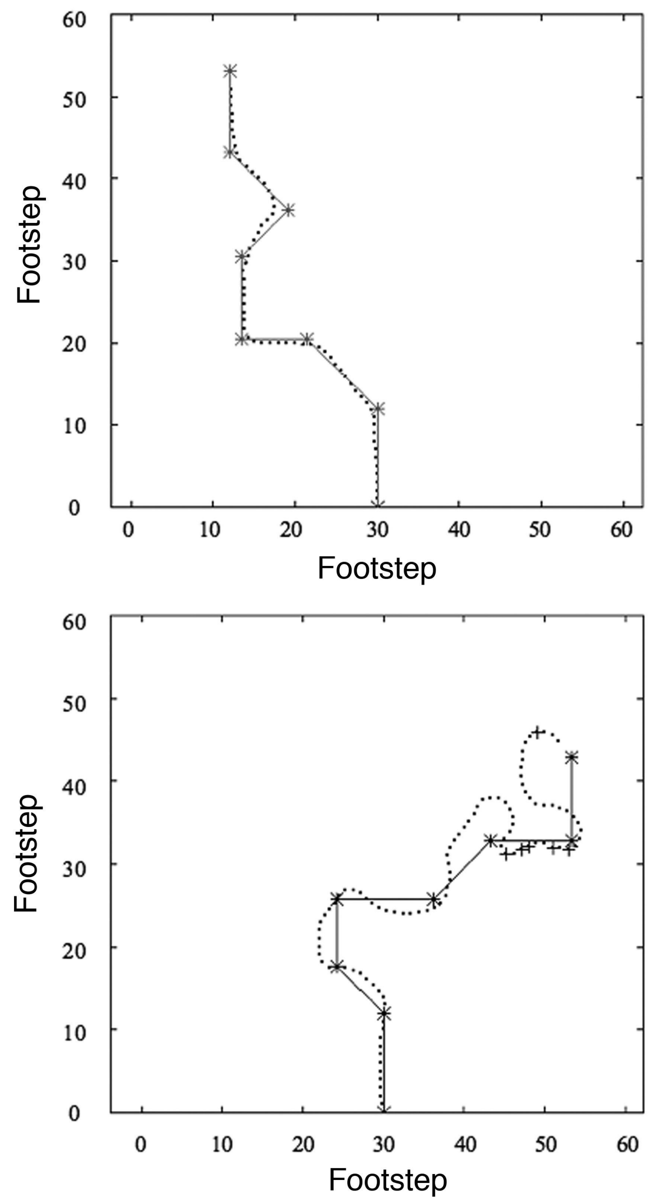

Figure 4. Sample trajectories for 2 participants guided by virtual sound (top) and spatial language (bottom). The space is scaled by footstep. Travel originates at the bottom center. The path is indicated by solid lines with asterisks at waypoints, the participant's trajectory is shown by dotted lines, and points of error in the *N*-back task are indicated by plus signs.

Table 1
Means and Standard Deviations of Difference in Distance (Steps) or Time (Minutes) for Trials With the N-Back Task, Relative to the Mean of Three Previous Trials With No Load, Shown by Trial Number and Guidance Mode (Virtual Sound, Spatial Language)

Condition and measure	*N*-back trial	*M*	*SD*
Distance			
Language	1	8.88	13.08
	2	7.28	15.30
	3	6.81	8.59
Virtual	1	9.28	26.01
	2	1.11	8.99
	3	1.13	5.70
Time			
Language	1	0.13	0.23
	2	0.15	0.24
	3	0.15	0.23
Virtual	1	0.13	0.51
	2	−0.02	0.22
	3	0.01	0.18

Table 2
Analysis of Variance on Distance

Source	*df*	*MS*	*F*	Effect size (Cohen's *f*)
Guidance mode	1	226.13	4.13	.26
Error	15	54.76		
Load	1	280.56	4.38	.27
Error	15	64.09		
Mode × Load	1	161.93	4.65*	.28
Error	15	34.85		

* $p < .05$.

[<.15] prevents us from accepting the null hypothesis). In contrast, using the *N*-back task resulted in increased distance and time when corrections were given by language: For distance, $t(15) = 2.26$, $p < .05$ (one-tailed), $d = 0.67$; for time, $t(15) = 3.04$, $p < .01$ (one-tailed), $d = 0.56$; these effect sizes are moderate.

The questionnaire data revealed that participants rated the virtual sound easier to use when also performing the *N*-back task, in comparison with spatial language with *N*-back (sign test; $p < .05$). Those favoring language in the questionnaire were not the same participants as the ones who had particular difficulty when transitioning to *N*-back with virtual sound.

Discussion

The present data augment and expand on previous studies described in the introduction, which have demonstrated the utility of direct perceptual cues to navigation and have compared those cues with speech-based guidance. This research provides convincing evidence that navigation guidance by an intrinsically perceptual modality is superior to guidance by spatial language with respect to cognitive load. Examination of performance in the absence of load showed no significant difference between guidance by virtual sound and language, with respect to time or distance traveled. The addition of a 1-back load, however, increased time and distance for spatial language. The magnitude of the increase had a moderate effect size with respect to both measures.

This effect occurred despite the participants' apparently having little difficulty with the navigation task, as assessed by their average number of footsteps. Footsteps traveled were, in most conditions, slightly less than the straight-line distance of 70, because of cutting corners. In an outdoor environment with physical movement along the terrain, researchers generally find that participants' trajectories are longer than the minimum path. For example, in the Loomis et al. (2005) study, the mean distance traveled for all displays was 62 m over paths of 50 m in length. Thus, the indoor foot stepping here assesses interference in a relatively undemanding navigation task and hence likely estimates a lower bound on the impact of spatial language.

An important question is how the *N*-back task, which was vibrotactile, interfered with verbal guidance. It is possible and indeed likely that some participants converted the locations of the vibrations to a verbal code. Rehearsal of the previous *N*-back location could have interfered with the processing of the verbal corrections, although those were reduced to three highly discriminable words ("left," "right," "straight"). That is, the interference with language could be attributable to the competing task's tying up language-specific short-term memory or what Baddeley (1986) has called the phonological loop. It is also possible that specifically spatial capacity was coutilized by language-based navigation and the *N*-back task. For example, the process of decoding language into spatial meaning may interfere with a spatial memory of the position of the vibration on the hand (see Baddeley, Grant, Wight, & Thomson, 1975). (One could argue, however, that the opposite should be true; that is, the directional nature of the virtual sound source could interfere with spatial coding on the hand.) Finally, central cognitive capacity may have been the locus of interference. These hypotheses are by no means mutually exclusive.

Our data have direct implications for the effectiveness of corrections during navigation without vision. Virtual sound appears to have an advantage with respect to cognitive load, as indicated by the reduced cross-interference with a competing task relative to spatial language. This finding must be weighed against the fact that virtual sound is more demanding with respect to technology.

The decision as to what kind of guidance should be used must also take into account how cognitive load plays out in terms of real-world performance. The deficit found here for language-based correction had little consequence for people navigating paths without curves over 70 footsteps. Because our design introduced the cognitive load after practice, it could, however, underestimate the effects of the load manipulation on unpracticed navigators. Moreover, as we have noted, the magnitude of the effect could be considerably magnified in more demanding circumstances, such as real-world situations with competing stimuli, more complex paths, and longer distances to travel, or if travelers had to decode more complex verbal instructions while en route. The consequences of error would be more critical in real-world navigation as well. It will be important for future work to compare the guidance modes in more demanding environments, as we have in the absence of a competing task (Marston et al., 2006). It would also be useful to investigate whether the superiority of virtual sound extends to other interfaces, for example, if used in conjunction with the haptic pointing interface (Loomis et al., 2005; Marston et al., 2006).

Another question for further research is whether extended practice with the navigation task would reduce or even eliminate the impact of cognitive load on performance with spatial language. Some of the participants in the present study showed no load effect, indicating that it is not inevitably of consequence. That number might well increase given further trials with the task. To the extent that practice alleviates the working memory demands associated with spatial language, we would expect blind navigators

Table 3
Analysis of Variance on Time

Source	*df*	*MS*	*F*	Effect size (Cohen's *f*)
Guidance mode	1	0.136	7.00*	.34
Error	15	0.019		
Load	1	0.096	3.38	.24
Error	15	0.028		
Mode × Load	1	0.082	5.44*	.30
Error	15	0.015		

* $p < .05$.

who habitually used it for guidance to be minimally affected. A testimony to the effects of practice can be found in a previous study (Marston et al., 2006) in which habitually mobile blind persons using a GPS-based guidance system for the first time out-performed sighted, blindfolded users, and some even approached the level of sighted travelers who had vision available while using the system.

The spatial language used here comprised only three cues, whereas the spatial precision of the virtual sound is essentially continuous. Simple language terms had previously been found effective (Loomis et al., 2005) and were used here with the intention of minimizing linguistic processing. However, this difference in the information provided by the guidance modes raises the question of whether participants hearing spatial language would have benefited from more precise terms. As was noted in the introduction, previous work (Loomis et al., 1998) compared simple corrective directions ("left," "right") with those that included the numerical value of deviation from the correct heading. With the feedback given every 1.5 s, the simpler language showed a negligible advantage in completion time, on the order of 10 s for a 3-min course. Thus, there is little evidence that more precise language would aid travelers when cognitive load is present.

We speculate that the present findings may have application beyond guiding navigation for the visually impaired. Users of GPS who travel with limited vision, such as soldiers traveling at night, could potentially benefit from virtual sound cues to navigation, as could those who do visually demanding work while remaining mobile, such as emergency teams or field workers gathering data. The reduced utility of vision in these contexts could render those involved functionally similar to users of navigation aids for the visually impaired. In support of this idea, Oving et al. (2004) noted that the advantage for 3-D audio over monaural sound, in warning pilots about simulated aircraft traffic, occurred particularly when their vision was occupied with a heads-down display of flight-path error.

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