Proceedings of the 9th International Conference on Low Vision, Vision 2008, Montreal, Quebec, Canada July 7 – 11, 2008

Environmental Learning without Vision: Effects of Cognitive Load on Interface Design

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Abstract. Blindfolded participants were guided along routes from two display modes: spatial language ("left," "right," or "straight") or spatialized audio (where the perceived sound location indicates the target direction). Half of the route guidance trials were run concurrently with a secondary vibrotactile N-back task. To assess cognitive map development, subjects performed a homing task from the route's terminus. As spatialized audio displays are processed perceptually, we hypothesized they would be less affected by increased cognitive load than language displays, which require cognitive mediation. In corroboration, results showed the secondary task had no effect on cognitive map performance for guidance by spatialized audio but led to significantly worse homing errors for guidance by spatial language. Spatialized audio was also reliably faster and more accurate than language for traversing the route. These results have important implications for the design of future navigation and guidance systems for visually impaired persons.

Keywords: blind navigation; cognitive mapping; assistive technology; cognitive load

1. Background

In 1985, Jack Loomis at the University of California envisaged the notion of an accessible GPS-based navigation system for the blind (Loomis, 1985). A hallmark of that system was the use of 3-D virtual sound, where the names of objects, landmarks, or choicepoints are heard, through headphones, as emanating from their physical location in the environment. Over the ensuing twenty plus years, this project has progressed from a concept, to a working prototype, to a full-blown research platform known as the Personal Guidance System (PGS). Behavioral studies with the PGS have focused on determining the best user interface, with several lines of research demonstrating the efficacy of virtual sound for supporting non-visual route guidance in both open field and neighbourhood settings (for a review of the evolution of the system and associated research, see Loomis, Golledge, Klatzky, & Marston, 2007).

This research has consistently shown that, compared to other presentation modes, 3-D virtual audio, referred to as spatialized audio (SA) displays throughout this paper, (1) led to the fastest and most accurate route guidance performance and (2) are judged by end-users to be the most preferable interface. In part, the advantage for SA displays is that they are perceptual, i.e., the user can directly hear the distance and direction of objects from a first-person perspective. By contrast, spatial language (SL) displays, as are often used in non-visual navigation systems, require cognitive mediation to interpret the verbal message, e.g., the target is in 15 feet at 2 o'clock. Reducing cognitive intervention is an important goal for any system designed to support blind navigation, as the ability to monitor the environment and stay updated when travelling requires significant cognitive effort when done without vision (Rieser, Guth, & Hill, 1986). Thus, perceptual interfaces are postulated to be particularly important for blind and low-vision persons, as they can provide spatial information about the environment in a way that does not compete for cognitive resources. Based on the assumption that spatial language displays take more working memory capacity to process the linguistic information than a spatialized audio display, we predicted that SA displays would be more effective in situations with greater cognitive load.

This question was addressed in a study by Klatzky and associates where subjects were guided along virtual routes using a spatialized audio or spatial language display (Klatzky, Marston, Giudice, Golledge, & Loomis, 2006). Importantly, on half of the trials, subjects performed a secondary N-back task during route guidance that required them to monitor vibrotactile pulses on three of their fingers. We used a 1-back paradigm; subjects had

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to indicate if a vibration occurred on the same finger as had the previous vibration. This haptic N-Back task has been shown to be similar to the well known visual version commonly used to assess working memory capacity (see Klatzky et al., 2008 for comparison). Following from our predictions, adding a concurrent N-back task to the SA condition did not significantly change route guidance performance from the no-load condition, but the addition of load in the SL conditions led to significantly slower and less accurate performance. These data support the view that use of an intrinsically perceptual interface is superior to spatial language for supporting route guidance with increased cognitive load.

The current study builds on the work by Klatzky and associates (2006) but addresses environmental learning and cognitive map development in addition to route guidance. Similar to the earlier work, comparison is made between spatialized audio and spatial language displays for navigating routes with and without a concurrent N-back task. However, the current design also includes a task requiring memory of the path travelled. Developing an accurate cognitive map is important as it allows for complex spatial behaviours such as detours, shortcuts, determination of novel routes, and recovery from disorientation. Blind people often have trouble with these tasks, presumably due to insufficient access of environmental information and the associated cognitive demands (Thinus-Blanc & Gaunet, 1997). As the SA display provides direct perceptual access to spatial information and is more effective in high load situations, we predict that it will show better performance on the cognitive mapping task than spatial language, especially in the presence of a secondary task. As everyday navigation involves many distractions, determining the non-visual display which is most effective in high cognitive load situations will have important utility for future development of navigation systems for the blind.

2. Method

Twenty volunteers, half female, participated in the study. All subjects gave informed consent and reported normal hearing and visual status.

The procedure involved having blindfolded participants walk along various 21-foot paths, consisting of 3 randomly ordered 5, 7, and 9-foot segments, which were laid out in a 14 x 19 space. The two turns created by placement of segment two, relative to segments one and three, consisted of combinations of 45, 90 or 135-degree angles. The task was to walk along the path (route guidance) and upon reaching the terminus, to turn to face the start point (called homing, used to assess the development of a cognitive map). Route guidance information was given, through headphones, from two presentation modes. From the start position, participants were guided between the waypoints (located at each of the vertices) using: (1) spatial language, where instructions about the direction of the next waypoint were given as left, right, or straight and (2) spatialized audio, where the direction of the next waypoint was heard as a tone emanating from its location. To assess cognitive load, half of the trials in each presentation condition included a secondary N-back task. On these "load" trials, subjects had to monitor vibrotactile pulses randomly applied to 3 of their fingers (digits 1, 3, and 5) and push a button when the same finger was stimulated twice in sequence. This 1-back task was performed simultaneously with route guidance.

This is a within subjects design, with participants running in a load and no-load condition with SA and SL guidance. Load and no-load trials were blocked by display mode, with load balanced within block and block order alternated between subjects. Altogether, participants walked fourteen paths, eight experimental routes and six practice routes (path order was randomized within subject). Two cameras were used for tracking the participant's position on the route and head rotations were monitored using an inertial sensor mounted on the headphones. This apparatus, shown in figure 1, allowed for updating the user's position as they walked and provided the appropriate output about the direction of waypoints. The physical routes were virtually rendered using the Vizard 3-d modeling software package (www.worldviz.com).

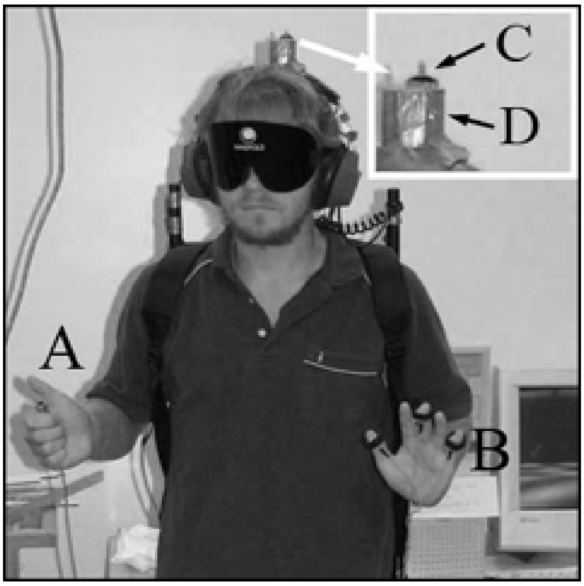

Fig. 1. Experimental Apparatus: (A) push button, (B) Vibrotactile stimulators on fingers, (C) LED used for camera tracking (inset), and (D) inertial sensor for tracking head orientation, (inset).

3. Results

Measures assessed during route guidance included: time to traverse the route and the distance walked, given as a percent of total route length. Cognitive map development was measured by homing turn error, i.e., the absolute difference between the angle turned and the actual angle between the participant's final heading and the start point. The primary findings of the experiment are shown in Figures 2 and 3. Two-way repeated measures ANOVAs comparing display mode (SA and SL) and load (N-back on or off) were conducted for the dependent measures of route distance, route time, and homing error. Main effects were observed with presentation mode for route distance $F(1, 19) = 18.533$, $P = < 0.01$, $\eta_p^2 = 0.49$; and time $F(1, 19) = 38.441$, $P = < 0.01$, $\eta_p^2 = 0.67$. As can be seen in Fig 2, both main effects showed an advantage for SA over spatial language. A main effect of load was also found for time, $F(1, 19) = 7.568$, $P = < 0.05$, $\eta_p^2 = 0.29$, but this load effect was primarily driven by the difference of load and no-load in the spatial language condition.

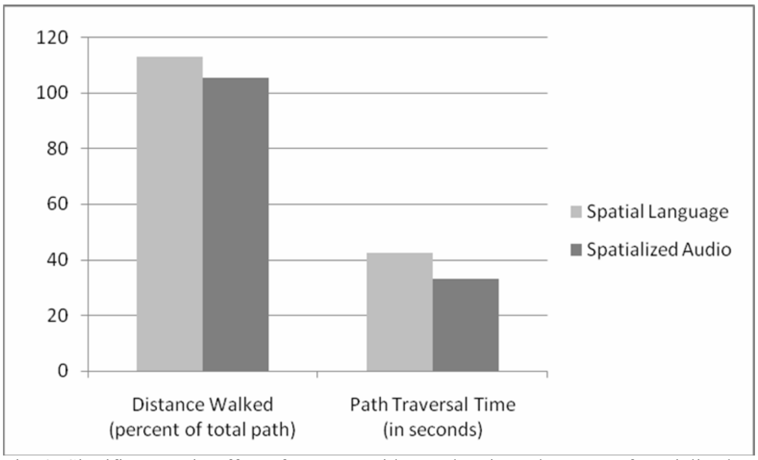

Fig. 2. Significant main effects for route guidance showing advantage of spatialized audio vs. spatial language for percent distance walked and path traversal time.

As is seen in Fig 3, an interaction between presentation mode and load was observed for homing error, $F(1, 19) = 6.209$, $P = < 0.05$, $\eta_p^2 = 0.25$. This interaction was as predicted, namely, there was one deviant condition with higher error, i.e., spatial language combined with load.

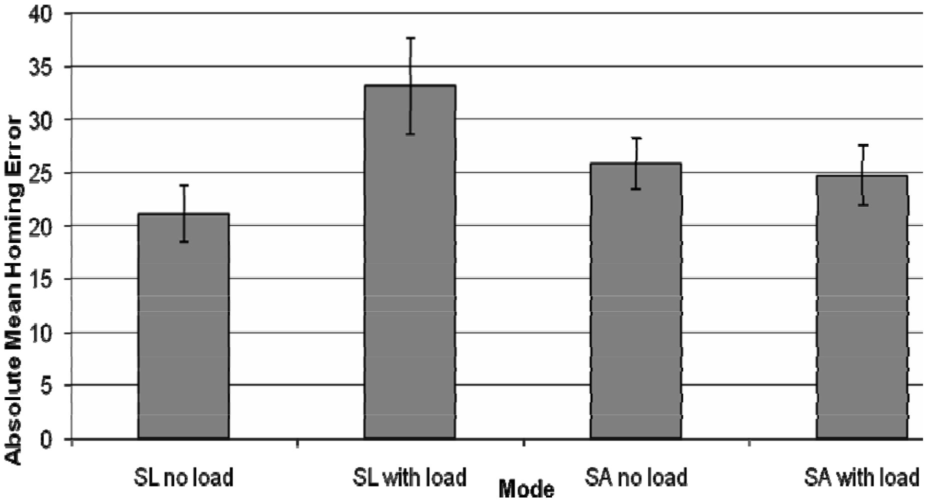

Fig. 3. Shows the interaction of spatialized audio and spatial language with load and no-load conditions; where inclusion of the secondary N-back task leads to a significant increase in homing error for SL, it has no effect on SA.

4. Discussion

This paper addressed the effect of cognitive load on route guidance and environmental learning. The primary interest of this study was performance on the homing measure, as this task required participants to remember the path as a whole (cognitive map). Since the homing angle requires determining the distance and direction of the start point from the route's endpoint, participants had to accurately update their position and orientation as they walked. In our previous work (Klatzky, 2006), we found that route guidance was better with a spatialized audio display than a spatial language display when done with a concurrent N-back task. As the homing task in the present experiment required more computation than simple route guidance, we postulated that this advantage would also manifest for cognitive mapping behavior. The interaction of mode and load for the homing error support this prediction. While performance did not differ between SA and SL no-load conditions, adding a secondary N-back task resulted in a significant performance diminution for SL but no decrement for SA. These findings suggest that the spatialized display, representing a perceptual interface, is in less competition for working memory demands than the spatial language display, which requires cognitive mediation. Indeed, all but one subject reported liking the SA condition better and felt that this presentation mode best facilitated development of a cognitive map.

The results of the route guidance measures demonstrated that people took less time and traveled more accurate routes when guided by spatialized audio information than by spatial language. In our previous study, we found an advantage for spatialized audio in the load conditions only. The general advantage of spatialized audio over spatial language found here indicates that a perceptual display is beneficial for route guidance both with and without additional memory demands.

Taken together, these findings extend our previous research with route guidance to cognitive map development, demonstrating the benefit of spatialized audio over spatial language for navigation with and without load. Since blind navigation often requires significant cognitive effort, the ultimate goal is to develop a display which supports the highest level of navigation performance and spatial knowledge acquisition while being minimally effected by other tasks requiring cognitive resources. To date, commercial speech-based navigation systems have only used language but the current results suggest that future development of this technology should consider inclusion of spatialized audio displays, both to support route guidance and cognitive map development. Finally, the finding that 19 out of 20 participants preferred the SA display provides important end-user input about the efficacy of this presentation mode as a non-visual interface.

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