In-Vehicle Spatial Auditory Displays
Reducing reaction times, errors, and cognitive load
to improve in-vehicle system usability and safety

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Introduction

In-vehicle systems can do much to improve both the driver experience and safety while driving. However, the plethora of new capabilities and services becoming available through in-vehicle systems can also have the opposite effect by adding to distractions and, more subtly, by increasing the cognitive load on the driver.

Spatial auditory displays (sometimes referred to by the unfortunate acronym: SAD) can help provide both a more agreeable and a safer driving experience. Among their benefits are reduction of cognitive load and shortening of driver reaction times. By providing drivers with auditory cues that associate different activities and instructions with specific locations, spatial auditory displays help drivers “intuitively” identify voices, the sources of instructions, and even the location and relative trajectory of danger. They can also reduce reaction times to application prompts and potentially dangerous roadway objects and events.
In lay terms, cognitive load can be defined as the amount of work a person’s brain is doing at any given time. Cognitive load affects, among other things, a person’s ability to learn, to respond to and interpret stimuli, and to perform even commonplace tasks. As Ton de Jong writes in “Cognitive load theory, education research and instructional design”

The basic idea of cognitive load theory is that cognitive capacity in working memory is limited, so that if a learning task requires too much capacity, learning will be hampered.1

Similarly, a person’s ability to successfully complete a task (such as a driver negotiating a turn in a busy intersection) will be hampered by his cognitive load. There is evidence suggesting that interference by a task of a different modality (e.g. verbal-auditory: listening to the radio or speaking on a phone) than the modality involved in the primary task (e.g. visual-spatial: negotiating traffic while making the turn) may cause less interference than does a secondary task (adjusting the radio2 or even identifying and reading direction signs3 while making the turn) of the same modality as the primary task. This view is the basis for the argument that it may be safer for a driver to use a hands-free telephone than a hand-held telephone while driving.

Though the media, legislators, researchers and interested organizations have focused—quite rightly—on the dangers of mobile phone use by drivers, mobile phones are only one, highly visible and easily identified contributor to a driver’s cognitive load. Les Hatton, for example, suggests that in Britain
Although it is impossible to quantify its effect on safety yet, the gradual proliferation in road signs may be causing problems of information overload for drivers, with some intersections having more than 16 signs.4

It is not our intention to contribute here to the complex and contentious debate over telephone use while driving. Suffice to note that there is little argument that, whatever its source, cognitive load does affect how a driver controls his vehicle. If this correlation between cognitive load and driver performance is true, then it should be possible to use technology that can help reduce the cognitive load on the driver to improve, not only the driver experience, but also driver performance and vehicle safety.

One such technology is spatial auditory displays (SAD). As well as increasing driver satisfaction with in-vehicle systems and applications, spatial auditory displays help reduce cognitive load, and may help improve driver performance by shortening response times and reducing errors.

**Spatial auditory displays**

Today, in-vehicle audio systems are designed so that users perceive all sounds emitted by most non-music applications as coming from a single location in the vehicle. In contrast, spatial auditory displays cause users to perceive sound as coming from different locations in a three-dimensional space. These perceived locations may be different positions inside the vehicle, or even locations slightly outside the vehicle.

Figure 2. Prompt localization using standard auditory display for phone and climate control applications.

Figure 3. Prompt localization using spatial auditory display for phone and climate control applications.
A standard auditory display and a spatial auditory display are illustrated in Figures 2 and 3, respectively. Both the vehicles illustrated have Speech Recognition (SR) systems that can be used to manage the vehicle climate control system and dial phone numbers. Figure 2 shows an SR system whose auditory prompts for both the climate control system and the phone are localized at the same position on the standard auditory display. Figure 3 shows the same prompts coming from different locations on the spatial auditory display, each position being associated with a specific application.

The ability of spatial auditory displays to help a driver associate an application or prompt with a specific location, and even effectively communicate dynamic spatial information associated with an object (e.g., current location and trajectory). This can be used in various ways to improve the user experience of current and future in-vehicle applications, with positive implications for the driver's cognitive load and driving performance.

**Spatial cues used by listeners**

Spatial auditory displays deliver acoustic cues, which the human auditory system can use to help it localize the source location of sounds. Some knowledge of the acoustic cues listeners use to identify sounds and their locations is, therefore, important for anyone who will be involved with implementing a spatial auditory display.

An adequate discussion of this topic would fill a few library shelves and is beyond the scope of this paper: the list below is not exhaustive, but it is a good starting point for anyone wishing to learn more about these acoustic cues.

- Onset disparities—differences of when a sound begins at the left and right ears
- Inter-aural Time Differences (ITDs)—the difference in phase of a sound between the listener’s two ears.
- Inter-aural Level Differences (ILDs)—the differences in the sound level at the ear directly in the path of the sound compared to the ear in the sound shadow produced by the listener’s head; the frequencies heard by the ear in the sound shadow will be lower than those heard by the ear directly in the path of the sound waves.
- Spectrum—the distribution of intensity of the sound across its frequencies
- Overall level—the intensity of the sound being heard
- Direct-to-reflected sound ratio—the intensity of the sound that reaches the listener directly relative to the intensity of the sound that is reflected off objects before reaching the listener
- Deltas from reference objects—differences in the aforementioned cues between the sound and a reference sound

**Different types of spatial auditory displays**

The degree to which a spatial auditory display can cause a user to perceive a sound at the desired location depends on its implementation. This
implementation depends on hardware (essentially the number, type, and location of speakers) and capabilities of the signal processing (e.g. wide-band versus standard signal). Table 1 lists vehicle audio system displays ranked by accuracy. Note that even with an ideal display the limits of human perception limit the precision with which location can be used to identify and differentiate prompts.

<table>
<thead>
<tr>
<th>More accurate</th>
<th>Less accurate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large array of loudspeakers</td>
<td>Single loudspeaker using monaural cues</td>
</tr>
<tr>
<td>Headphones or two loudspeakers with cross-talk cancellation</td>
<td></td>
</tr>
<tr>
<td>Surround sound system (e.g., surround sound 5.1 audio)</td>
<td></td>
</tr>
<tr>
<td>Stereo signals with balance and fade control</td>
<td></td>
</tr>
<tr>
<td>Mono signal with balance and fade control</td>
<td></td>
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</tbody>
</table>

Table 1. Vehicle audio system hardware implementations, in descending order of localization accuracy.

### Improvements to driver performance

Spatial auditory displays can improve driver performance because it can improve the human-machine interface the driver uses to communicate with his vehicle. These improvements, essentially error reduction, shortening of response times, and better comprehension, enable better task performance and, hence, a) lessen the effort required to perform a driving-related or a non-driving-related task, and b) reduce judgement errors allowing for quicker and more accurate performance of driving and secondary tasks.

### Error reduction

The judgement errors spatial auditory displays can help reduce include identification errors, location errors, and navigation manoeuvre errors.

### Identification errors

Identification errors are errors the user makes when identifying the application, object or event that produces a sound (prompt, instruction, warning, etc.). Though users often eventually figure out the correct source of a sound, this identification requires effort and costs time.

Spatial location is a mnemonic device that helps users remember items by associating them with a spatial location. The human auditory system automatically processes acoustic localization cues at a lower cognitive level to identify position, and users in a vehicle will remember that any sound coming from a specific location belongs to the associated application, object or event. Thus, as it is a reliable clue to the source of the sound and hence to the action required by the user, spatial location can help reduce the time and effort the driver needs to correctly identify a sound, understand what response is expected of him, and correctly perform the required action.
Location errors
Location errors occur when the user's judgement of a sound source's location is wrong, or significantly different than, it's true or intended location. For example, a driver may incorrectly locate an approaching emergency vehicle if his window is open and the vehicle's siren is reflected from nearby building. By controlling the acoustic cues delivered to the user, however, spatial auditory displays can help the driver locate the emergency correctly and with less effort.

Navigation manoeuvre errors
Navigation manoeuvre errors occur when the driver fails to correctly execute a navigation manoeuvre. Spatial auditory displays help reduce these types of errors in two ways. First, they provide redundant information on the location of the manoeuvre. Instead of just prompting with verbal instruction to the driver to “Turn right in 100 meters”, they can provide redundant information about the location of the manoeuvre by localizing the prompt in space. Second, they can convey trajectory information about the manoeuvre, using apparent motion of the prompt to convey, for instance, a "slight right" as opposed to a "sharp right".

Improved driver response times
Spatial auditory displays can reduce the time a driver needs to identify the application providing a prompt and to fix an object's location. With sounds emitted by, say, the telephone, always coming from one location, and those emitted by the climate control system always coming from another, a driver can instantly recognize the source of a sound or instruction. A spatial auditory display providing spatial cues to an object's location, such as an approaching emergency vehicle, reduces the time required by the driver to correctly locate the object. Especially if the object is another vehicle on a collision path, time gained can mean the difference between a close call and an accident!
Improved speech comprehension

Spatial auditory displays can improve speech comprehension in noisy vehicle environments by placing speech at a different location (or locations if there are multiple voices on the far-end of the conversation) than noise sources such as the vehicle tires, engine, etc. This is sometimes referred to as the “cocktail party effect”\(^1\).

This placement of speech at specific locations in the vehicle also produces a better “sense of presence” for far-end voices, which can be crisply localized directly in front, for example, instead of existing as a smeared spatial image somewhere down in the foot well.

The benefits of improved speech comprehension are not limited to less listening effort and improved quality of the current telephone conversation. Especially if combined with techniques such as wide-band telephony, spatial auditory displays can also help reduce driver distraction\(^5\) because the easier it is to understand who is speaking and what is being said, the fewer shared cognitive resources such as working memory and attention are required for the conversation, and therefore, the greater the resources available for correctly performing other tasks, such as driving the vehicle.

Reduced visual-manual distraction

Spatial auditory displays can help reduce visual-manual distraction, helping the driver keep his eyes on the road. Spatial auditory cues help speed visual

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\(^{1}\) The “cocktail party effect” refers to a listener’s enhanced ability to focus on a specific voice while ignoring other voices and noises because of information provided by the directionality of the sounds.
target acquisition. In the vehicle, this means that auditory prompts at specific locations can be used to quickly direct the driver’s eyes a) to specific visual information on the dashboard display, and b) back to the forward roadway when significant roadway events occur. Both these types of prompts help reduce the intervals during which the driver’s eyes are looking at instrumentation and information displays, and increase the time they spend looking at the road ahead.

![Spatial Auditory Display](image)

Figure 5. A spatial auditory display aiding drivers by warning them of an approaching emergency vehicle.

**Impact on driver performance**

Ultimately, the value of spatial auditory displays in vehicles is that they help the driver easily, rapidly and correctly identify who or what is speaking or emitting a sound, the location of the sound and its meaning. These contributions to improved interaction between the driver and both in-vehicle applications (navigation, telephone, infotainment) and the vehicle itself and its context (notices, warnings, etc.) speeds reaction times, reduces visual distraction, and reduces the cognitive load on the driver, hence, improving both the driving experience and safety.

**Conclusion**

As more and more applications are introduced into vehicles, the need to minimize their impact on the driver’s ability to perform his primary task—drive safely—will only increase. Spatial auditory displays will prove invaluable both for facilitating human-machine interaction in the vehicle and as an enabling technology for new in-vehicle applications. Spatial auditory displays can provide the auditory cues humans use to “intuitively” identify and understand object and event locations, trajectories and meanings, and they can be used.
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to improve the driver’s situational awareness of what is going on within, and around his vehicle. Thus, spatial auditory displays can help reduce the cognitive load on drivers, leaving more cognitive resources available for driving, as well as reducing driver fatigue over time. Spatial audio displays may very well be one of the best kept secrets for improving the user experience and fighting driver distraction.

References

6 S. Pennock and P. Hetherington, “Wideband Speech Communications: the Good, the Bad, and the Ugly”, *Audio Engineering Society 36th International Conference*, 2-4 June 2009, Dearborn, Michigan, USA.

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