AUDITORY AND HEAD-UP DISPLAYS FOR ECO-DRIVING INTERFACES

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ABSTRACT

Eco-driving describes a strategy for operating a vehicle in a fuel-efficient manner. Current research shows that visual eco-driving interfaces can reduce fuel consumption by shaping motorists' driving behavior but may hinder safe driving performance. The present study aimed to generate insights and direction for design iterations of *auditory* eco-driving displays and a potential matching head-up visual display to minimize the negative effects of using purely visual head-down eco-driving displays. Experiment 1 used a sound card-sorting task to establish mapping, scaling, and polarity of acoustic parameters for auditory eco-driving interfaces. Surveys following each sorting task determined preferences for the auditory display types. Experiment 2 was a sorting task to investigate design parameters of visual icons that are to be paired with these auditory displays. Surveys following each task revealed preferences for the displays. The results facilitated the design of intuitive interface prototypes for an auditory and matching head-up eco-driving display that can be compared to each other.

1. INTRODUCTION

From 1990 to 2007 transportation has been responsible for a 45% growth in CO_2 emissions, with a predicted rise of an additional 40% by 2030 [1]. Emerging innovations in vehicles are aimed at improving fuel economy (FE) to reduce emissions and reduce cost of ownership. Saving fuel can immediately reduce cost of operation and environmental impacts. *Eco-driving* is a readily available technique that shapes driving behaviors increase FE without reliance on automotive advances such as body or engine changes. Research shows that driving styles such as rapid acceleration and deceleration hinder eco-driving; and therefore, are used as prompts for eco-driving displays [2].

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Herein we discuss efforts to develop low workload displays for eco-driving, notably, through auditory displays and visual head-up displays.

2. Current Eco-Driving Interfaces

Fuel Economy Driver Interfaces (FEDIs) have been shown to improve FE by up to 20% [3]. However, nearly all research and development of FEDIs has focused on visual displays [4], with most being head-down, dashboard displays. Figure 1 shows the TOYOTA Eco-Indicator, an eco-indicator bar that tells you how economically you are driving. When the driver is accelerating excessively, the bar will stretch beyond the "eco zone" and start flashing. That means it is likely that more fuel than needed is being used. Unfortunately, driving is a demanding task when it comes to visual attention [5] and since most current FEDIs also rely on visual resources, this may create a competition for additional resources. Evidence supports the case that current visual FEDIs can distract drivers from attending to the road, increase workload, and in effect, hinder driving performance [4].

2.1. Design Considerations

While current dashboard-based FEDIs may increase distraction, there are other approaches to design eco-driving interfaces that limit driver distraction while simultaneously shaping motorists' driving behaviors. In order to increase driver safety and FE, head-up displays (HUDs) and auditory displays should be explored.

Figure 1: The TOYOTA Eco-Indicator: A visual-only dashboard display of fuel economy.

2.1.1. Auditory Displays

Wickens' Multiple Resource Theory (MRT) [6] provides valuable insights for this investigation. This multitasking theory proposes that the limited capacity of working memory creates a bottleneck when resources are exhausted [7]. The bottleneck leads to a reduction in working memory resources for a primary task, when a secondary task of the same modality is introduced. As Wickens [6] suggests, when such homogeneous tasks are imposed, performance declines due to mental workload overload. For example, a visual display on a car stereo (a secondary task) may limit the resources available for the visual needs of the (primary) driving task. The theory suggests that in this instance, secondary tasks should be done via a different modality [6]. One potential modality in this case is the auditory modality.

Auditory displays for In-Car Infotainment Systems (ICIS) have been shown to increase a driver's visual attention on the primary driving task (driving), as compared to visual in-vehicle displays [8]. Results from a driving simulator and eye-tracking experiment showed sonification assistance, with respect to the ICIS, significantly reduced eye-movements towards the ICIS, thereby reducing participants' reaction times in the primary driving task. This finding corroborates the multiple resource theory model of multitasking by enhancing driving performance with reduced visual tasking [8]. Previous research has also resulted in similar conclusions for interfaces that used sound within the vehicle context, including increased visual attention on the driving task [9] and better driving performance [10].

While no audio-only FEDI is found in the literature or commercially, a FEDI including complimentary audio to a visual display has been studied [4]. That prototype multimodal display included a lower frequency tone (512 Hz) to indicate insufficient acceleration and a higher frequency tone (predominantly at 1770 Hz) to indicate excessive acceleration. Preferences revealed that participants tend to report displays with complementary audio as more effective at advising eco-driving behavior than visual-only displays [4]. In addition, behavioral measures showed that time spent looking at the road increased and drivers' pedal error (having the pedal outside the ideal range) decreased when using a system with added audio [4].

Unlike visual displays, auditory displays have the added capability to convey information to the driver, regardless of head or body position [11]. Auditory displays also allow for a wide range of information to be communicated to a driver through many dynamic acoustic parameters (in addition to speech sounds): frequency, timbre, range, register, and rhythm [11]. As Nees and Walker [12] suggest, an empirical investigation could determine the best mapping, scaling, and polarity of such sound features for a FEDI. Mapping, scaling, and polarity must be optimized to ensure that workload is not increased as a result of added auditory displays [13]. Further, driving performance and workload can be affected by annoyance [13]. When mapping acoustic parameters, it is important to consider trade-offs involving the effect of annoyance associated with some sounds [12].

2.1.1. HUDs

In-vehicle visual displays inherently demand more visual scanning time, thereby increasing cognitive load and distracting users from the driving task [14]. Empirical research has emphasized the importance of visual display placement in vehicles. The lower a display is positioned vertically (i.e., the farther below the windshield it is), the more severely driving performance is decreased, seen through increased reaction time and decreased target detection performance [15]. However, lane position can be maintained, even when attention is focused on in-vehicle displays, if the distance from the display to the outside line of sight is minimal [16]. This finding suggests that drivers can learn to manage dual-task load using peripheral vision, allowing them to maintain lane performance. Therefore, issues experienced using traditional visual displays may be overcome using head-up displays (HUD), which project information onto the vehicle windshield [17].

Simulator studies found that under both low- and high-difficulty driving conditions, drivers exhibit faster reaction times to task-related detection, such as speed limit sign changes, while attention is focused on the HUD [18]. Driving performance measures, such as variance of lateral acceleration, steering wheel turning (degrees), and acceleration are also improved while attending to the HUD as opposed to traditional head-down displays [18].

When designing HUDs, it is important to consider the trade-off between too much clutter and scanning-time cost. If too much information is displayed in the HUD, far-field vision becomes compromised and may cause attentional tunneling, which will decrease driving performance [19]. Therefore, it is recommended that the visual design reduce clutter by only including information that is pertinent to the task. As with all displays, ill-informed HUD designs could add to distraction, increased workload, and confusion [17]. Likewise, it is important to investigate the best mapping, scaling, and polarity of HUD designs to ensure the visual displays match a user's mental model of the system [20].

The amount of information communicated through visual displays has been studied in the context of FEDIs. A comparison of three different visual designs found that displays with greater information content were judged as more supportive for eco-driving behavior [4]. In that study a "foot-and-pedal" display showed current pedal error; a gauge display showed the rate of change of pedal error; and a dot display showed pedal error only. Results from behavior tests revealed speed maintenance with the gauge display was better than with the foot, whereas acceleration performance was better with the foot than with the gauge.

3. THE CURRENT RESEARCH

The primary goal of this study is to find patterns and preferences in the results that aid both auditory and HUD design decisions for future displays. The design guidance and prototypes this study yields for future research could result in advancements for both FE and driver safety. The present study suggests current visual heads-down eco-driving interfaces impose an additional visual demand to the already visually heavy task of driving. Although Young, Birrell, and Stanton [14] called for the development of eco-driving displays that decrease visual distraction, few examples of such research exist. There is a need to investigate the design of in-vehicle auditory and HUD displays that safely communicate how driver behavior affects fuel efficiency [2].

3.1. Types of Displays

3.1.1. Types of information displayed

There are two non-mutually exclusive categories of information that the displays in this study fall under: continuous and intermittent, and inform and instruct.

3.1.1.1 Continuous and Intermittent Displays

The optimal temporal structure of a display system is an important aspect of design. In a recent study of truck drivers' preference regarding visual FEDIs, both *continuous* and *intermittent* display prototypes were tested in a simulator [21]. Participants showed unique preferences for continuous and intermittent display types alike. A majority of participants noted that speed guidance (continuous display) was useful, easy to understand, and made controlling speed easier. A majority also found the performance feedback (intermittent display) positive, liking the feedback as an incentive to drive "eco-friendlier" [21]. In terms of an auditory display, a constant or continuous sound representing FE may generate annoyance [12]. Therefore, the current study assesses the best design parameters to be used in both a continuous and an intermittent display type for each modality (visual and auditory). For the purpose of this study, intermittent displays are designed to communicate the overall FE of a driving trip. In contrast, continuous displays are designed to give dynamic information about the current fuel economy.

3.1.1.2 Inform and Instruct Displays

In both the auditory and visual domain, this study proposes two primary display types for conveying information to the operator: *inform* and *instruct* displays.

Inform displays present information about a user's current behavior, increasing situation awareness to their current performance, allowing them to shape their behaviors to fit the task goals. In the current research domain, such a display might tell the driver if he or she is accelerating too fast or too slowly to meet the eco-driving goals.

On the other hand, *instruct* displays directly communicate how the user should change their behavior to accomplish the task goals. This means that users do not need to use this information to compare to the goal state but are instead told exactly what to do. So, for someone trying to increase their fuel economy an instruct display might tell a driver to accelerate more slowly.

Previous research has investigated a similar concept, finding that displays presenting more persuasive information (displays focused on convincing the user to change their behavior) were perceived as less useful and more difficult [22]. The instruct displays in this study (i.e., telling drivers how to behave), are analogous to those persuasive displays.

3.2. Experiment 1 (Auditory Matching) Overview

This participatory design study iteratively investigated sound parameters for the design of an auditory eco-driving interface. Sound-sorting methods provide an efficient way to categorize and evaluate sound design parameters, especially when there is a large number of stimuli [11, 23]. Participants matched sound parameters to eco-driving icons and descriptions. Participants completed a forced choice matching task with three sections (one for each display type): inform, instruct, and overall FE. Inform and instruct eco-driving concepts were investigated as continuous methods of display, whereas overall FE was an intermittent display. The frequency data collected through the number of times a sound was matched with a description of an eco-driving behavior established acoustic mappings, scaling, and polarity for each type of eco-driving display. In addition, a survey after each section of the forced choice task determined preferences for display types.

With the results of Experiment 1, the auditory design process took into account certain capabilities and limitations of sound characteristics inside the vehicle. A key limitation in vehicles is acoustic masking related to vehicle and road noise [12]. Experiment 1 results and special acoustic considerations facilitated the design of an intuitive and unambiguous auditory interface prototype to be used in future driving simulator research.

3.3. Experiment 2 (Visual Matching) Overview

This participatory design study investigated visual parameters for an iterative design of a HUD eco-driving interface. Card-sorting methods were also used as a way to categorize and evaluate visual designs. In the card-sorting, visual icons were matched to eco-driving words or concepts. There were three forced-choice matching tasks: instruct, inform, and overall FE. The frequency data collected through the number of times a sound was matched with a description of an eco-driving behavior established mappings, scaling, and polarity for each type of eco-driving display. Again, a survey following each task determined preferences for each type of display: instruct, inform, and overall FE.

In addition to the Experiment 2 data, the HUD design process took into account special visual design considerations, such as compromising far-field vision and attentional tunneling [17]. Experiment 2 results and special design considerations facilitated the design of an intuitive and usable HUD prototype for future driving research.

3.4. Research Questions and Hypotheses

Research Question 1: Which acoustic parameters are most useful and preferred for an auditory display of eco-driving concepts?

Research Question 2: Which visual parameters are most useful and preferred for a HUD of eco-driving concepts?

Hypothesis 1: Participants will display a higher preference for *inform* compared to *instruct* displays.

4. EXPERIMENT 1

4.1. Participants

Participants included 41 students (19 male) with an average age of 20.2 years (SD=1.8). Participants were required to be 18 or older to ensure they had some driving experience and were required to have normal or corrected to normal vision and hearing to control for abilities needed to perform the sound card-sorting task. They held a driver's license for an average of 3.7 years (SD=2.0).

4.2. Materials

The sound-sorting program used in the current study was written using HTML, jQuery, and Bootstrap's framework. Using Ableton Live music production software, sounds themselves were designed for acoustic parameters of interest. Surveys were constructed and executed online. Sounds were heard through SONY MDR-V150 Dynamic Stereo Headphones.

Three types of auditory displays were used in the study: earcons, auditory icons, and speech. *Earcons* are abstract sounds with no prior association (e.g., musical phrases), but the matching frequencies were expected to yield relationships between acoustic parameters and perceptions of constructs [11, 23]. *Auditory icons* are sounds that are ecologically associated (e.g., engine noises), and *speech* consisted of text-to-speech generations [12].

4.3. Procedure

Upon arrival participants signed consent forms and then sat at a computer, put on headphones, and began the sound-sorting program. The program started with a tutorial so that participants could become accustomed to the drag-and-drop procedure used to sort sounds.

There were three within-subject trials: one each for informational, instructional, and overall FE displays. The independent variables were the acoustic parameters presented on each slide: ADSR (attack, decay, sustain, release), audio effects, instruments (timbre), auditory icons, triads (musical chords), voices, scales (speech), register (musical octaves), range (distance between frequencies), and tempos. Sound parameters varied randomly within each trial. The first and second trials were randomly assigned. These trials investigated acoustic parameters for a continuous display. One trial asked participants to match sounds to driving *instruction* icon-word pairs, shown in Figure 2. Second, sounds were matched to icon-word pairs that *inform* a driver of current driving behavior status. A third trial investigated acoustic parameters for an intermittent display by having participants match sounds to a metric of overall FE.

Figure 2: Inform display trial from Experiment 1.

Next, a survey asked participants which type of auditory displays (earcons, auditory icons, or speech) they believe to be most informative, least distracting, and would prefer. After both trials one and two were completed, there was an additional survey assessing user preference for an *inform* versus an *instruct* display. Following the third trial, a survey asked participants which type of overall FE display they believed to be most informative, least distracting, and would prefer: earcons, auditory icons, speech, earcons and speech, or auditory icons and speech.

4.4. Results

4.4.1. Sound card sorting results

Frequencies and percentages for sound-to-concept matches were calculated for the various acoustic parameters in each category. Due to the exploratory nature of the study, frequency counts were found to be the most useful type of data. Not all acoustic parameters resulted in high matching agreement between participants, but for some there were clear trends. As seen in Figure 3, there was high agreement among listeners that a musical phrase starting at note C0 and ascending to note C5 matched best to the concept of *accelerate a lot*, whereas a descending phrase from note C5 to C0 matched best to the concept of *decelerate a lot*. Similarly, C1 ascending to C4 and C2 to C3, matched best to *accelerate a little*, whereas C3 descending to C2 and C4 to C1 matched best to *decelerate a little*. The trend found in this particular set of sounds reveals auditory design guidance: an accelerate instruction is best matched to an increasing frequency; a decelerate instruction is best matched to a decreasing frequency; and range (distance between notes) can represent the magnitude of change in acceleration instructions. Using frequencies recorded in the three trials, an equivalent analysis was conducted for each acoustic parameter and auditory display studied: ADSR, audio effects, instruments, auditory icons, triads, voices, scales, register, range, and tempos. High matching agreement was determined and recorded (Table 1).

	Instruct	Inform	Overall Eco Preformance
ADSR	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Slow Attack, High Sustain	Fast Attack, Low Sustain	High Sustain
	Decelerate	Excessive Acceleration	High Fuel Economy
	Fast Attack, Low Sustain	High Sustain	Fast Attack
Effects	Accelerate	Insufficient Acceleration	Low Fuel Economy
	High Freq. EQ	Reverb, Low Freq. EQ	Delay, Reverb
	Decelerate	Excessive Acceleration	High Fuel Economy
	Low Freq. EQ, Delay	Delay, Distort	High Freq. EQ
Instru-ments	Accelerate	Insufficient Acceleration	Low Fuel Economy
	String, Xylophone	Bass	Brass, Marimba
	Decelerate	Excessive Acceleration	High Fuel Economy
	Bass, Marimba	Brass	Xylophone
Icons	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Engine Freq. Up	Engine Freq. Down	Short Guzzler
	Decelerate	Excessive Acceleration	High Fuel Economy
	Engine Freq. Down	Engine Freq. Up	Long Guzzler
Triads	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Major Ascending	Aug. & Major Descending	Aug. & Dim. Descending
	Decelerate	Excessive Acceleration	High Fuel Economy
	Minor Descending	Major & Aug. Ascending	Major Ascending
Voices	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Female	Female	Female
	Decelerate	Excessive Acceleration	High Fuel Economy
	Male & Female	Male & Female	Female
Scales	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Major & Minor Ascending	Major Descending	Minor & Blues Descending
	Decelerate	Excessive Acceleration	High Fuel Economy
	Major & Minor Descending	Minor Ascending	Major & Minor Ascending
Register	Accelerate	Insufficient Acceleration	Low Fuel Economy
	C4 > C3 > C2	C2 > C3 > C4	C2 > C3 > C4
	Decelerate	Excessive Acceleration	High Fuel Economy
	C2 > C3 > C4	C4 > C3 > C2	C4 > C3 > C2
Range	Accelerate	Insufficient Acceleration	Low Fuel Economy
	C0-C5 Ascending	C5-C0 Descending	C5-C0 Descending
	Decelerate	Excessive Acceleration	High Fuel Economy
	C5-C0 Descending	C0-C5 Ascending	C0-C5 Ascending
Tempos	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Fast, Increasing	Decreasing, Slow	Slow, Decreasing
	Decelerate	Excessive Acceleration	High Fuel Economy
	Decreasing, Slow	Increasing, Fast	Fast, Increasing

Table 1: Auditory parameters resulting in high matching agreement between participants.

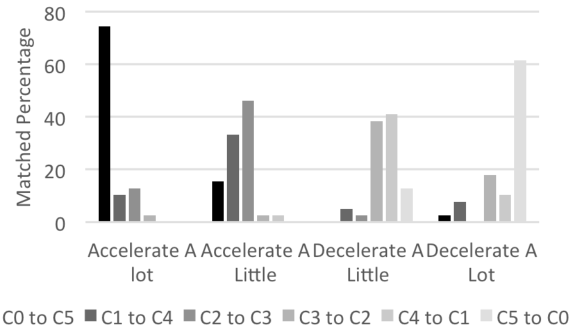

Figure 3: Match percentages of various ranges from Experiment 1 *instruct* trial.

4.4.2. Survey results

Response frequencies from the surveys following each trial show that auditory icons were generally reported as most distracting across all trials (see Table 2). The auditory icons were ecologically associated, meaning they resembled engine noises. This is compounded with acoustic masking and therefore, earcons and speech were considered best for an eco-driving auditory display. Participants were generally in agreement that speech was more informative than earcons in both the instruct and inform trials. However, there was no consensus as to which was preferred. In the overall FE trial, there was agreement that a display with *both* earcons and speech would be most informative and preferred.

Responses were higher for *instruct* displays over *inform* displays across all three measures. A chi square binomial probability test showed the *instruct* display had higher ease of understanding (p=0.001). This means that in auditory FEDIs instruct information was preferred.

Inform	**Earcon**		**Icon**	**Voice**	
Most Informative	3		12	25	
Least Distracting	18		8	14	
Most Preferred	14		8	18	
Instruct	**Earcon**		**Icon**	**Voice**	
Most Informative	3		9	26	
Least Distracting	16		6	16	
Most Preferred	11		3	24	
Overall Eco-Driving	**Earcon**	**Icon**	**Voice**	**Earcon & Voice**	**Icon & Voice**
Most Informative	4	2	8	19	6
Least Distracting	12	7	9	8	3
Most Preferred	8	1	8	15	7
Instruct vs Inform	**Instruct**			**Inform**	
Ease of Use	30			10	
Least Distracting	22			18	
Preference	23			17	

Table 2: Preference survey frequencies from Experiment 1.

5. EXPERIMENT 2

5.1. Participants

Participants were 46 students (24 males) with an average of 20.1 years old (SD=1.7). Participants had the same age, vision, and hearing requirements as in Experiment 1. Participants had held a driver's license for an average of 3.3 years (SD=1.9).

5.2. Procedure

Participants sat at a computer and began the icon-sorting program, starting with a tutorial to become familiar with the procedure. Participants then matched each icon to an eco-driving concept by dragging and dropping.

There were three within-subject trials. The independent variables were the types of icons presented on each slide: vertical continuous bars, vertical segmented bars, horizontal continuous bars, horizontal segmented bars, arches, up-down arrows, forward-back arrows, colors, leaves, trees, and shoe-on-pedal (Table 3). Images within each trial were randomly varied. The first and second trials were randomly assigned. These two trials investigated visual icons for a continuous display. One trial asked participants to match icons to driving *instructions*, as shown in Figure 4. In a second trial, icons were matched to words that *inform* a driver of current driving behavior status. The third trial investigated sound parameters for an intermittent display by asking participants to match sounds a metric of overall FE.

Following each of trials one and two, a survey asked participants which type of visual displays they believed to be most informative, least distracting, and would prefer as a user.

After both trials one and two were completed, there was an additional survey assessing user preference for an *inform* versus an *instruct* display. Subsequent to the third trial, a survey asked participants which type of overall FE display they believed to be most informative, least distracting, and would prefer as a user.

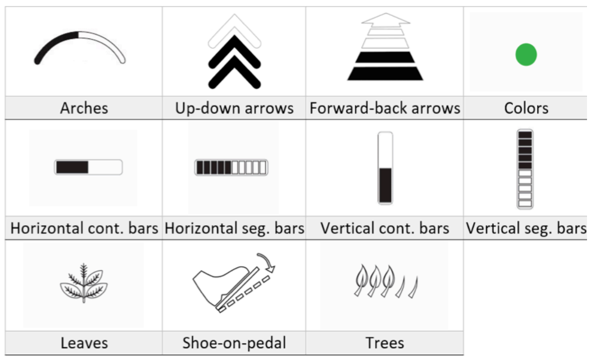

Table 3: An example of each type of image presented on the slides in Experiment 2.

Figure 4: *Instruct* display trial from Experiment 2.

5.3. Results

5.3.1. Matching results

Frequencies and percentages for icons-to-concept matches were calculated for the various visual parameters in each category. It was not necessary to perform inferential statistical analyses because this study is exploratory in nature [23]. Most visual parameters did have high matching agreement between participants, indicating clear trends. As seen in Figure 5, there was high agreement among viewers that the color red matched best to the concept of *decelerate a lot*, the color orange matched best to the concept of *decelerate a little*, yellow matched best to *appropriate acceleration*, light green matched to *accelerate a little*, and dark green to *accelerate a lot*. Using frequencies recorded in all three trials, a similar analysis was conducted for each parameter and type of visual studied: vertical continuous bars, vertical segmented bars, horizontal continuous bars, horizontal segmented bars, arches, up-down arrows, forward-back arrows, colors, leaves, trees, and shoe-on-pedal. High matching agreement was recorded as seen in Table 4.

	Instruct	Inform	Overall Eco Performance
Vertical Cont. Bars		Insufficient Acceleration	Low Fuel Economy
		Down	Down
		Excessive Acceleration	High Fuel Economy
		Up	Up
Vertical Seg. Bars	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Up	Down	Down
	Decelerate	Excessive Acceleration	High Fuel Economy
	Down	Up	Up
Horizontal Cont. Bars		Insufficient Acceleration	
		Left	
		Excessive Acceleration	
		Right	
Horizontal Seg. Bars		Insufficient Acceleration	
		Left	
		Excessive Acceleration	
		Right	
Arches		Insufficient Acceleration	
		Less fill	
		Excessive Acceleration	
		More fill	
Arrows (Forward/Back)	Accelerate		
	Forward		
	Decelerate		
	Back		
Arrows (Forward/Back)	Accelerate		
	Forward		
	Decelerate		
	Back		
Arrows (Up/Down)	Accelerate		
	Up		
	Decelerate		
	Down		
Colors	Accelerate	Insufficient Acceleration	Low Fuel Economy
	Green>Light Green>Yellow	Green>Light Green>Yellow	Red>Orange>Yellow
	Decelerate	Excessive Acceleration	High Fuel Economy
	Red>Orange>Yellow	Red>Orange>Yellow	Green>Light Green>Yellow
Leaves			Low Fuel Economy
			Less leaves
			High Fuel Economy
			More leaves
Trees			Low Fuel Economy
			Less trees
			High Fuel Economy
			More trees
Shoes/Pedals	Accelerate		
	Low angle		
	Decelerate		
	High angle		

Table 4: Visual parameters resulting in high matching agreement between participants.

5.3.2. Survey results

As shown in Table 5, in the overall FE trial, the leaf icons and horizontal segmented bars were seen as least informative, most distracting, and least preferred. In the inform trial, the arch icons were reported as most informative, least distracting, and most preferred. The foot-to-pedal icons were most distracting while the up-down arrow icons were preferred in the instruct trial. In all other measures there were no clear participant preferences.

Frequencies were higher for instruct displays over inform displays across all three trials. Chi square binomial probability tests of responses showed that the inform icons had significantly greater ease of understanding (p=0.024), were the least distracting (p<0.001), and most preferred (p<0.001).

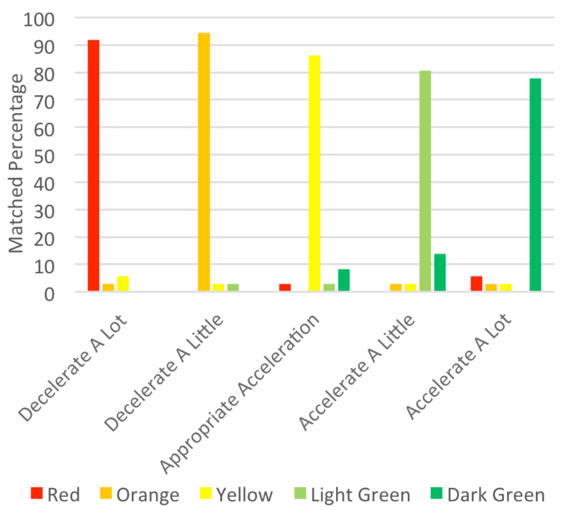

Figure 5: Match percentages of various colors from Experiment 2 instruct trial.

Inform	Arches	Vertical seg. bars	Horizontal seg. bars	Vertical cont. bars	Horizontal cont. bars
Most Informative	25	6	10	1	2
Least Distracting	21	8	6	4	5
Most Preferred	28	6	5	1	4

Instruct	Arrows (up/down)	Arrows (left/right)	Vertical seg. bars	Foot & Pedal
Most Informative	13	10	8	13
Least Distracting	15	9	15	5
Most Preferred	17	10	10	7

Overall Eco-Driving	Tree	Leaves	Vertical seg. bars	Horizontal seg. bars
Most Informative	16	9	16	4
Least Distracting	12	5	19	9
Most Preferred	15	8	16	6

Instruct vs Inform	Instruct	Inform
Ease of Use	15	29
Least Distracting	11	33
Preference	9	35

Table 5: Preference survey frequencies from Experiment 2.

6. GENERAL DISCUSSION

The results of Experiments 1 and 2 comparing *instruct* and *inform* display types expose a potential hurdle for design. Acoustic parameters that matched to *instruct* icon-word pairs generally revealed an opposite polarity to those matched to *inform* icon-word pairs (Table 1). For example, in the instruct trial, participants matched ascending pitches to accelerate, and descending pitches to decelerate. In the *inform* trial, participants matched ascending pitches to excessive acceleration and descending pitches to insufficient acceleration. Here the polarities are opposite because *instructing* a driver to accelerate and *informing* a driver of insufficient acceleration is delivering information about the same driving phenomenon. However, these two analogous concepts were mapped to opposite acoustic parameters: ascending and descending frequencies, respectively. Decelerate and excessive acceleration (similar concepts) were also mapped to opposite acoustic parameters: descending and ascending, respectively. This may actually make it simpler to develop auditory interfaces for this task, as the designers do not have to worry about issues of cross coding of the displays.

The same pattern can be seen in the Experiment 2 icon-to-concept matching results (Table 4). For example, a vertical bar in the up position matched best to accelerate, but was also matched to excessive acceleration. Similarly, a vertical bar in the down position matched best to decelerate, but was also matched to insufficient acceleration. The opposite polarities between inform and *instruct* displays could be problematic for a design, which draws from both. This issue must be considered in future multimodal displays.

Experiment 1 surveys found *instruct* auditory displays preferable, while Experiment 2 surveys found *inform* visual displays preferable (*Hypothesis 1*). However, a multimodal display using *instruct* sounds and *inform* visuals would present incongruent information with opposite polarities. This could lead to user confusion and distraction in the driving environment. These findings should also be used to advise future multimodal design.

6.1. Human-centric and System-centric Displays

Human-centric and system-centric displays are two approaches to showing information to drivers, whether it is information based on human parameters (human-centric), or system parameters (system-centric). In the current study both the instruct and inform displays were human-centric because they directly told the driver how to engage or change driving behavior or told them about their eco-driving behaviors, both of which were focused on the human. However, the overall FE information was a system-centric display as it displayed a metric describing the fuel economy within the system to the driver. These factors should be considered further in future work.

6.2. Major findings and future research

The purpose of this study was to find patterns and preferences that contribute to both an auditory and HUD design. Major findings include the high auditory and visual matching frequencies (Tables 1 & 4; *Research Question 1 & 2*). These trends, along with survey results indicating preferences, directed our design of intuitive, usable, and unambiguous auditory and HUD FEDIs. Future research will evaluate how research-driven designs compare to commercially used visual dashboard displays. This next-step research will investigate these prototypes in a driving simulator study. The primary measures will include eco-driving behavior, eye behavior, subjective workload, and driving performance. Future research should also consider other age groups to ensure that matching of the displays does carry over age groups, or to determine what differences are seen between age groups. Results from these works could serve as a verification of the design guidance in this study and will help determine what types of displays effectively and safely communicate fuel efficiency to shape driver behavior.

7. ACKNOWLEDGMENTS

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