Encouraging eco-driving: the case for accelerator–based haptic information

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ABSTRACT

Over the course of two driving simulator experiments, various types of eco-driving support were investigated. In the first experiment, sensory mode was examined. Driving performance in conditions with visual, auditory, and vibrotactile stimuli, and all combinations thereof, were compared with each other, and with performance when driving without information. The stimuli aimed at discouraging excessive acceleration, and at encouraging an enhanced coasting phase when approaching events necessitating deceleration. Following results from that experiment, the second experiment looked only at vibrotactile information for the support of enhanced coasting phases. As with experiment one, the vibrotactile alerts were presented via the accelerator pedal; however, where in experiment one coasting alerts were provided at a fixed eight seconds before a slowing event, experiment two manipulated this timing (using four, eight, and twelve second thresholds). The general conclusion was that vibrotactile information, presented through the accelerator pedal, represents a promising and as yet under investigated method of supporting eco-driving and, moreover, that coasting as a fuel-saving strategy is more deserving of support via in-vehicle information than is the discouragement of harsh accelerations.

KEYWORDS

Eco-driving, driving simulator, in-vehicle information, haptic information

Introduction

The academic community has long been aware that the amount of fuel used for a particular journey is dependent on the way in which a vehicle is driven (e.g., Evans, 1979), and that ‘eco-driving’ (the term that covers the behaviours that result in lower fuel consumption) can be supported with in-vehicle information (e.g. Barkenbus, 2010). The great majority of research on in-vehicle eco-driving support focusses on visually presented information; however, if one should follow Wickens’ (2008) multiple resource theory, one could argue that further loading the visual mode, in a safety-critical environment that already heavily depends on visual information, is likely to result in increases in workload, which will in turn have an effect on performance and safety (e.g., Recarte, 2003). Providing information through other sensory channels could circumvent this issue, and research investigating the presentation of haptic stimuli (i.e., stimuli that excite the sense of touch) via the accelerator pedal has shown promising results (see Petermeijer et al., 2015, for a review).

In addition to the workload argument, there are theoretical justifications for using haptic information presented through the accelerator pedal. Ecological Interface Design (e.g. Rasmussen & Vicente, 1989) is a design philosophy based on (among other things) the principle that a system’s interface should support operator reasoning and action at the lowest form of cognitive control, the perceptual-motor level. Rather than requiring from the user a process of effortful reasoning, the interface should support automatic responses to time-space signals. A cognitive task (requiring concerted conscious processing) should be transformed into a perceptual task (requiring simple stimulus-response actions) with well-designed alerts and interaction methods. Notably, the approach argues that the operator should be able to act directly on the display. In our previous work (McIlroy & Stanton, 2015) we found that expert eco-drivers achieved their fuel efficiency goals through carefully considered use of the accelerator pedal, in particular in the timings of pedal depression and foot removal, hence according to the EID theoretical argument (of combining action and observation surfaces), haptic information presented through the accelerator pedal should better support eco-driving behaviours than information presented through other locations and sensory channels (see McIlroy & Stanton, 2015; 2017, for more detailed discussions of this).

When specifically searching for eco-driving focussed research on haptics, a number of studies present themselves, each of which describes benefits to performance following the introduction of in-vehicle information. For example, in Birrell et al. (2013), the only study (to our knowledge) to use vibrotactile information rather force- or stiffness-feedback, excessive accelerations were discouraged; Jamson et al. (2013) supported ‘idealised’ acceleration and cruising control behaviours; Hajek et al. (2011) fostered early action to upcoming events; and Azzi et al. (2011) encouraged efficient accelerator position profiles across a journey.

In addition to investigating haptic information, Azzi et al. (2011) also made comparisons with a visual system; they found that the haptic condition incurred significantly lower control activity than the visual. Staubach and colleagues (Staubach et al. 2014a; 2014b) also made comparisons between haptic, visual, and a combination of the two, finding benefits for the combinations. Moreover, these researchers looked specifically at coasting, i.e., the act of moving forward without accelerator pedal depression (taking advantage of the momentum of the vehicle; this could be in or out of gear). Like in Hajek et al.’s (2011) research, support for early action to upcoming events proved to have merit in terms of efficiency gains. Finally, Jamson et al. (2015) made comparisons not only between visual and haptic feedback, but auditory as well. The auditory alerts were, however, only complimentary; they were not used on their own. As such, a full comparison of the effect of information across the three primary sensory modes is still lacking.

Given our own previous work on eco-driving and the theoretical justifications of in-vehicle haptic information (McIlroy & Stanton, 2015), the relative dearth of in-vehicle information research looking at all three sensory modes, and the on-going need to reduce the burden of private road transport on emissions volumes and energy use, we set out to develop and test a system for the support of eco-driving, one that would be both effective (in supporting safe, fuel-efficient driving) and acceptable (in terms of user satisfaction).

Experiment One

A driving simulator experiment was designed to compare the effects on eco-driving performance of information presented in each of the primary sensory modes, i.e., vision, audition, and touch, and all the possible combinations thereof. Following our own previous work (McIlroy & Stanton, 2015), two classes of behaviours were identified for in-vehicle support; the avoidance of harsh accelerations and the use of enhanced coasting phases. Both classes of behaviour relate to use of the accelerator pedal; the former involves minimising instances of excessive accelerator pedal depression; the latter involves having the driver remove their foot from the accelerator pedal in advance of events requiring deceleration.

To discourage excessive acceleration, a stimulus was presented when pedal depression exceeded 70% (an adaption of Birrell et al’s 2013 approach). The stimulus (or combination of stimuli) would be continuously presented for as long as depression exceeded that threshold. To encourage coasting, a stimulus was presented at eight seconds (judged acceptable in pilot testing) before a deceleration event; this was either a traffic light, stop sign, tight bend, or a road block. Stimuli were provided only if the accelerator pedal depression was greater than zero and the vehicle was traveling faster than the speed necessitated by the event (with target speeds dependent on the event in question). As with acceleration advice, stimulus presentation was continuous for as long as conditions were satisfied.

Vibrotactile feedback was presented via an array of six 3V vibrating motors attached to the back of a metal plate affixed atop the accelerator pedal. The visual (a red light) and auditory (a 400Hz tone) stimuli came from a box placed on the dashboard, to the right of the steering wheel.

The 30 participants (17 males, 13 females, aged from 23 to 59) drove 11 different routes, each lasting around 9 minutes, summarised in Table 1. The NASA-RTLX (Hart & Staveland, 1988) was used to measure workload and the Van der Laan Acceptance Scale (Van der Laan, 1997) to measure perceived usefulness of and satisfaction with the system. A variety of objective driving metrics were taken, including time taken, fuel used (calculated by the simulator software), mean, maximum, and standard deviation of throttle position, standard deviation of brake pedal use, total brake use (total area under the curve of brake pedal input by time), distance spent coasting, and excessive acceleration (i.e., product of the magnitude of throttle position when over the 70% threshold and time spent over that threshold).

Table 1: Summary of procedure

<table>
<tr><th>Day</th><th>Trial number</th><th>Description</th><th>Feedback</th><th>Route</th></tr>
<tr><td rowspan="5">1</td><td>1</td><td>Simulator training</td><td>None</td><td>Same for all participants</td></tr>
<tr><td>2</td><td>Baseline trial</td><td>None</td><td rowspan="10">Randomised across participants</td></tr>
<tr><td>3</td><td>Experimental trial – participants informed of eco-driving focus and asked to drive economically</td><td>None</td></tr>
<tr><td>4</td><td>Experimental trial</td><td rowspan="7">Any of the following; V, A, H, V+A, V+H, A+H, V+A+H</td></tr>
<tr><td>5</td><td>Experimental trial</td></tr>
<tr><td rowspan="6">2</td><td>6</td><td>Experimental trial</td></tr>
<tr><td>7</td><td>Experimental trial</td></tr>
<tr><td>8</td><td>Experimental trial</td></tr>
<tr><td>9</td><td>Experimental trial</td></tr>
<tr><td>10</td><td>Experimental trial</td></tr>
<tr><td>11</td><td>Learning effect assessment</td><td>None</td></tr>
</table>

Notes: V = visual, A = auditory, H = haptic, + denotes a combination of the feedback types indicated

Experiment One: Results

Due to non-normality, NASA-RTLX, Van der Laan usefulness and satisfaction scores, and the Excessive Acceleration variable, were analysed using Friedman's Test, with post-hoc analyses performed using Wilcoxon Signed Ranks tests. All other variables were analysed using a repeated-measures multivariate analysis of variance (MANOVA). Based on driving performance in the baseline trial, participants were split into two groups; high baseline fuel use and low baseline fuel use (the fuel use statistic having been calculated by the simulator software). This median split (15 in each group) allowed for testing of the information's effect on people of differing underlying driving styles (i.e., more or less economical). All statistical analyses used two-tailed tests and a 5% alpha level.

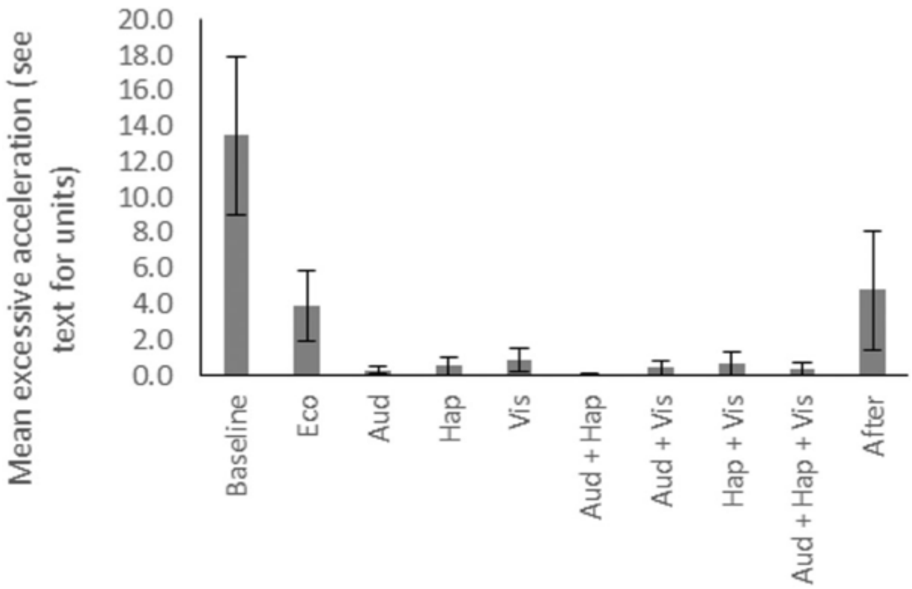

Figure 1: Mean excessive acceleration figures, with 96% confidence intervals

For excessive acceleration (Figure 1), the Friedman test indicated significant differences between conditions ($X^2_{(9)} = 102.857$, $p < 0.001$). Simply asking participants to drive economically had a significant effect on behaviour (baseline differed significantly to the eco condition); however, presentation of stimuli significantly increased this effect in all but the visual only and visual/haptic trials. Finally, visual information alone was significantly less effective at reducing harsh accelerations than were trials involving auditory, or auditory and haptic information together.

Regarding subjective measures, no differences were found for NASA-RTLX workload scores. Friedman tests did, however, reveal significant differences for both Van der Laan usefulness scores ($Q^2_{(9)} = 65.973$, $p < 0.001$) and satisfaction scores ($Q^2_{(9)} = 89.505$, $p < 0.001$). Results are shown in Figures 2 and 3. Regarding usefulness, visual information was the only type *not* rated as significantly more useful than the total lack of information given in the after trial. In terms of satisfaction scores, auditory information, and any combination containing it, was rated as significantly less satisfying than any combination *not* including the auditory stimulus.

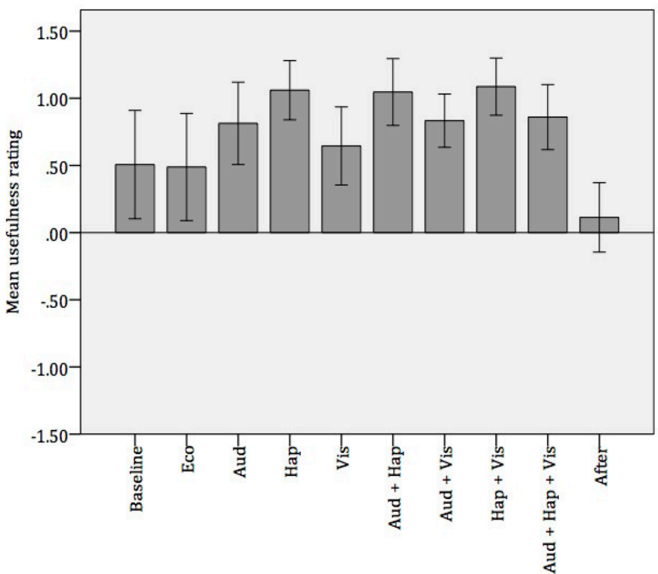

Figure 2: Usefulness scores

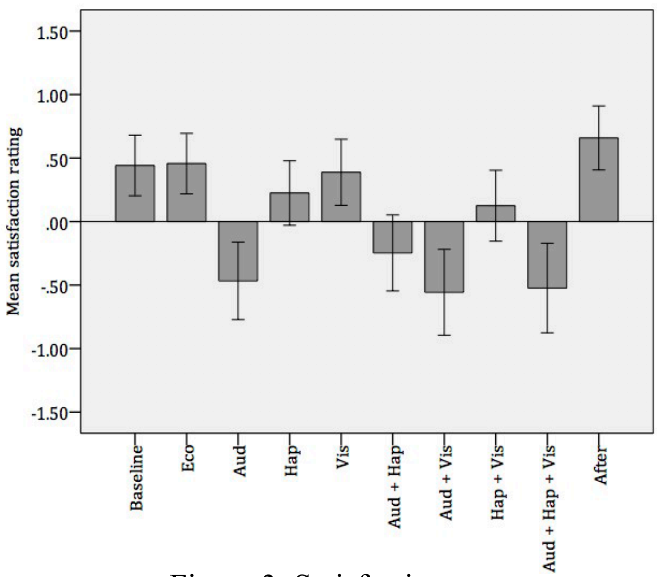

Figure 3: Satisfaction scores

For the objective driving measures, the MANOVA revealed a significant main effect for treatment (i.e., feedback type), $V = 1.298$, $F_{(72,1152)} = 3.100$, $p < 0.001$, partial $\eta^2 = 0.161$. This allowed for subsequent univariate analyses of variance to be undertaken for each dependent variable, all of which were found to be significant (see McIlroy & Stanton et al., 2016). The analysis also revealed a significant interaction effect for baseline fuel use group; $V = 0.701$, $F_{(72,1152)} = 1.538$, $p = 0.003$, partial $\eta2 = 0.088$.

The same pattern of results was shown for most measures; participants changed their behaviour upon being asked to drive efficiently (eco trial), behaviour that persisted until the after trial, where it reverted almost back to baseline performance. Figure 4 is indicative of the trend for *almost* all measures. The exception was Distance Coasting, shown in Figure 5. Simply asking participants to eco-drive did not have them produce this behaviour; additional feedback was required. For the interaction effects between the groups using more or less fuel in the baseline trial, analyses revealed significant differences for time taken, mean and standard deviation of throttle position, and fuel used. The pattern was the same across all variables. In the eco and after trials, those that used more fuel at baseline performed differently to those that used less fuel at baseline (i.e., less efficiently); under feedback conditions, those differences were greatly reduced or eliminated. An additional pattern was that in the visual only trial the higher fuel use group were less affected by feedback than the lower fuel use group; this trend was seen for each of the variables for which significant interaction effects were found. The visual stimulus was more likely to be ignored by the less economical drivers; auditory and haptic were not.

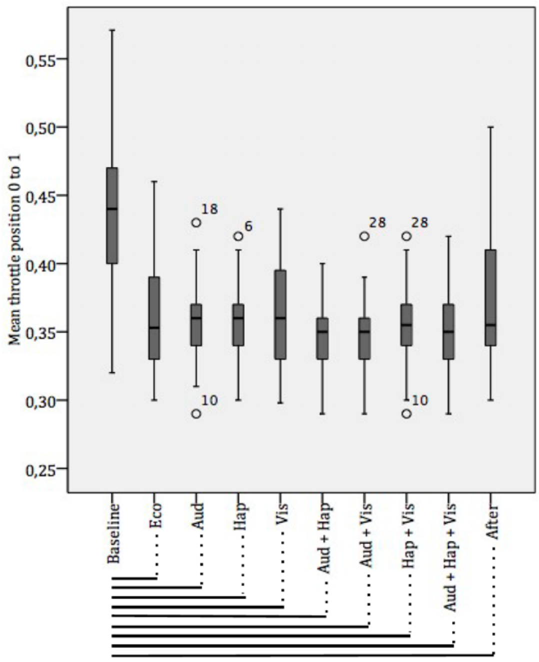

Figure 4: Mean accelerator pedal position, with 95% confidence intervals displayed. Solid lines underneath display significant comparisons

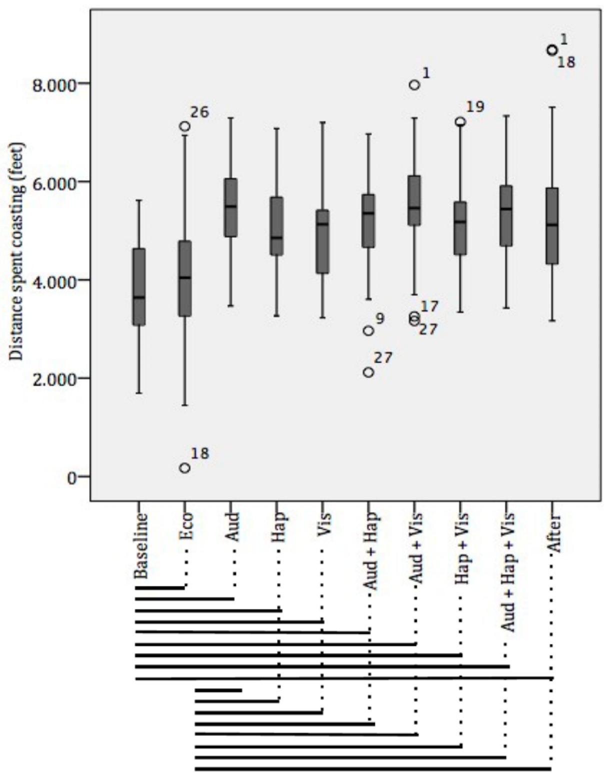

Figure 5: Distance spent coasting, with 95% confidence intervals displayed. Solid lines underneath display significant comparisons

Experiment Two

The second experiment represented a direct progression from the first, focusing purely on vibrotactile information. Not only was it effective in experiment one (across all participants it was more effective than visual information), but, and equally importantly, it was deemed acceptable by participants. Although auditory feedback also encouraged compliance, its low satisfaction ratings were unacceptable; as research from the medical domain demonstrates (Block et al. 1999), annoyance undermines the effectiveness of any system, as the user will ignore it or turn it off.

Experiment two also focussed only on coasting behaviours. Results from experiment one showed that upon being asked to eco-drive (i.e., upon activation of an eco-driving goal) participants spontaneously exhibit reduced instances of excessive acceleration, without the need for additional information. This was not the case for enhanced coasting; these behaviours were only exhibited upon the presentation of additional information specifically encouraging them. If a driver is turning on an *optional* eco-driving assist system, as such an in-vehicle device would be, they will likely already have an efficiency goal activated. We argue that it would be more beneficial to provide additional in-vehicle support only for those behaviours that are *not* spontaneously produced, rather than for a behaviour that is performed anyway upon activation of an efficiency goal. This way we minimise the volume of additional in-vehicle information to which the driver is subjected.

The main question that experiment two addressed, therefore, was that of stimulus lead times; just how far ahead of a deceleration event should a coasting support alert be presented? This question was also asked by Staubach and colleagues (2014a; 2014b), at least in part. They tested two stimulus timings, one giving advice earlier than the other. The early advice supported longer coasting phases, but was less well received by participants. Thus, our main hypotheses were that, 1) longer lead times would incur lower satisfaction ratings, and 2) longer lead times would encourage longer coasting phases and, therefore, lower fuel consumption. Eight seconds was chosen in experiment one after extensive pilot testing; experiment two used this, and lead times of four and twelve seconds, representing equidistant steps either side.

Each of the 24 participants (14 males, 10 females, aged from 23 to 60) had previously participated in experiment one. The same route was driven six times; two training sessions and one baseline trial with no additional information, and the three feedback trials (i.e., with information presented at 4, 8, or 12 seconds ahead of the deceleration event). The route took approximately five minutes to complete, and the order of feedback trials was randomised and counterbalanced across participants. This represented the independent variable; the dependent variables were the same as in the first experiment, with the difference that rather than excessive acceleration, a measure of total acceleration was used (the area under the curve created by accelerator position plotted against time). An additional set of questions was also included after each feedback trial, one of which asked whether participants thought information came too late, at the right time, or too early (on a scale from -4 to +4).

Experiment Two: Summary of Results

Data for all objective measures satisfied necessary conditions for the use of parametric statistical analyses, hence a MANOVA was applied. This revealed significant differences between conditions; $\Delta = 0.182$, $F_{(24,\ 180.42)} = 6.009$, $p < .0005$, partial $\eta^2 = .43$. Subsequent univariate tests revealed significant differences between conditions for all the variables measured, and pairwise comparisons (all made with Bonferroni corrections) resulted in a wide variety of significant differences between conditions. Figure 6 displays results for distance coasting, and Figure 7 for total accelerator usage.

The long lead time condition took significantly longer to complete than baseline, short, and medium lead-time conditions. No other conditions differed significantly from each other for this variable. In terms of Fuel Use, none of the conditions differed significantly from one another. In contrast, in the long lead-time condition significantly less fuel was used than in any other condition.

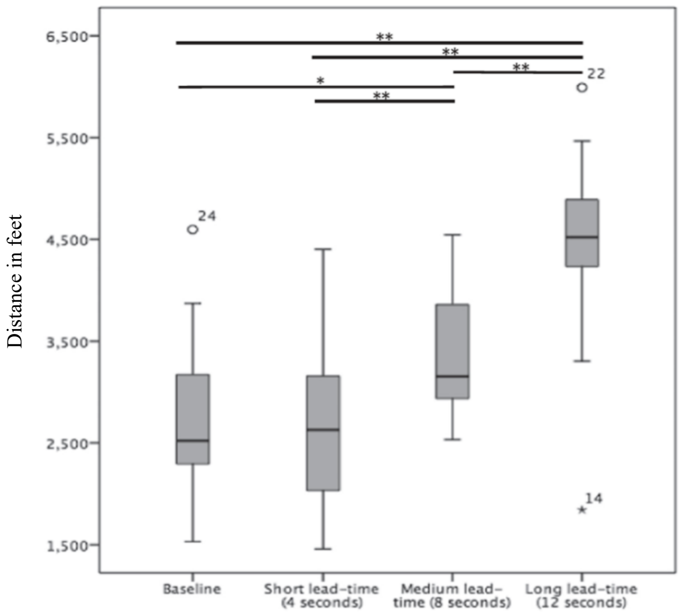

Figure 6: Distance spent coasting, by condition. Upper lines indicate statistically significant comparisons (*p< .01, **p<.005)

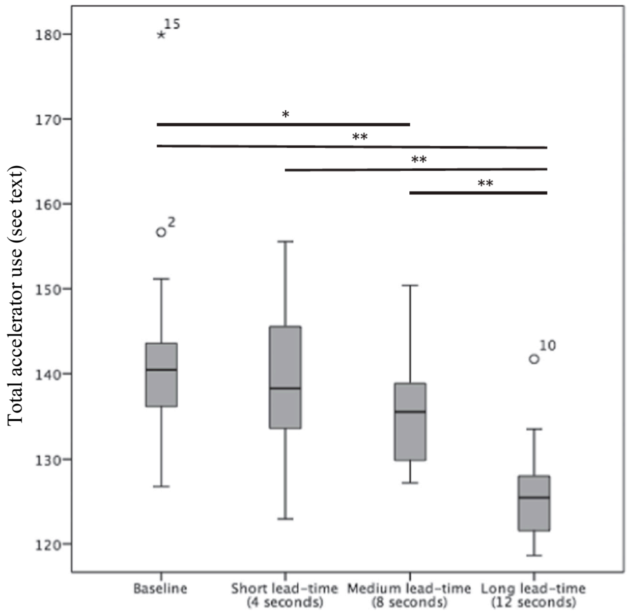

Figure 7: Total accelerator usage, by condition. Upper lines indicate statistically significant pairwise comparisons (*p<.01, **p<.005)

Regarding the subjective measures, the short lead time stimulus performed poorly. For satisfaction scores the only significant finding was that the short lead-time condition was considered significantly *less* satisfying than the baseline condition (in which no additional alerts were presented). In terms of usefulness, the medium lead-time condition was rated as significantly more useful than the short, while the long lead-time condition was rated as significantly more useful than either the baseline or short lead-time conditions.

Finally, for the question asking participants whether they thought the alert came at the right time, too early, or too late (on a scale of -4 to +4), it was found that participants rated the short lead-time condition as the *least* well-timed; the stimulus came too late, i.e., to close to the event necessitating deceleration. The medium and long lead-time conditions attracted similar ratings, though in opposite directions; the former was rated as coming slightly too late, the latter slightly too early.

Discussion

Results from experiment one mirrored those found elsewhere in the literature (e.g. Evans, 1979; Jamson et al. 2015); people significantly change their behaviour when simply asked to drive economically. Regarding harsh accelerations, although further discouraged by in-vehicle alerts (as in Birrell et al. 2013), these behaviours were already spontaneously reduced when driving with an efficiency goal (in the 'eco' trial). Given the significant added benefit of the alerts encouraging enhanced coasting (a behaviour *not* spontaneously produced upon asking people to drive efficiently), we conclude that it is this type of eco-driving behaviour alone (of the two classes studied here) that most deserves in-vehicle support. The car is already an information rich environment; hence, we should be prudent when suggesting additions to that environment. Given the fact that visual information was less effective across all participants, and that auditory alerts were universally disliked, we further conclude that it is vibrotactile coasting support that is most deserving of this additional in-vehicle support.

Although data from neither experiment one nor two can support claims regarding workload (cf. Wickens, 2008), the accelerator pedal based haptic alerts were indeed effective in encouraging eco-driving behaviours (as was also seen by, e.g., Hajek et al. 2011, Azzi et al. 2011, Jamson et al. 2013, Staubach et al. 2014a, 2014b). Results are therefore in line with the Ecological Interface Design (EID) theoretical discussion used to justify the vibrotactile feedback (see McIlroy & Stanton, 2015); however, as auditory alerts were equally effective (despite being universally disliked), more work is necessary to untangle the theory. To determine whether information provided at the site of control truly does foster faster, more automatic responding than information presented at an incongruous site, or in a different sensory mode, would likely require a more basic science approach (e.g. laboratory- rather than simulator-based). To answer these questions would likely help to further our basic understanding of human perception and action, but would be far less generalisable to the driving domain than experiments conducted in a high-fidelity driving simulator.

Regarding the practical need for specific types of in-vehicle eco-driving support, it is interesting to consider our results alongside those of Franke et al. (2016). Of the hybrid-vehicle drivers they interviewed, 18% suggested that certain efficiency boundaries could be displayed via detailed haptic or vibrotactile feedback presented through the accelerator pedal. This idea also resonates with the theory behind EID (see, e.g., Rasmussen & Vicente, 1989) regarding boundaries of operation; in this instance, it is the boundary between efficient and inefficient deceleration that the system tested here intends to display. This is likely to be especially important in vehicles with regenerative braking, particularly electric vehicles. Their enhanced deceleration has been shown to support one-foot driving (e.g., Labeye et al. 2016), a style whereby careful control of the accelerator results in the mechanical brake being unnecessary in normal driving situations, with use of vehicle momentum and energy re-uptake being central to maximising efficiency.

Regarding experiment two, results were clear. For medium and long lead times, not only did the distance spent coasting increase, but both the total accelerator pedal usage and the amount of fuel used decreased significantly (11% between baseline and long lead time conditions). This supports the hypothesis that long lead times lead to improved eco-driving performance; more use of momentum results in less use of the accelerator pedal, and therefore greater overall efficiency. It was also shown that if one provides a stimulus *too* close to an event, performance can even decrease (see Figures 6 and 7, above). In terms of user acceptance, our results suggest that there may be an optimum of around 10s (half way between the medium and long lead-times), but that different users have different preferences. Given these results, we would therefore argue that the threshold be modifiable by the user down to a lower limit.

Finally, this research has shown the benefits of vibrotactile alerts, rather than force or stiffness feedback, something that, to our knowledge, has previously been investigated only by Birrell et al. (2013). The technology required to guide a system such as that tested here may not yet have reached full maturity; however, with the progression of projects like Continental's eHorizon (see Continental, 2017), and research into vehicle to vehicle and vehicle to infrastructure communication moving forward (see, e.g., Ndashimye et al. 2017), such technology is not far off. Understanding the best way to present that information to the driver is a question that deserves attention now.

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