Influencing Greater Adoption of Eco-Driving Practices Using an Associative Graphical Display

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Substantial energy savings during the use phase of internal-combustion and electric automobiles can be achieved by increasing eco-driving behavior, particularly reduced acceleration and braking. However, motivating widespread adoption of this behavior is challenging due to incompatibility with drivers' values and priorities, and disassociation between drivers' actions and observable consequences. Informational approaches, e.g., training programs and educational campaigns, are either difficult to scale up or largely ineffective, with drivers reluctant to make long-term changes. Alternatively, behavior can be influenced by redesigning the context within which the behavior occurs. Such an intervention must be effective across demographics and underlying behaviors to achieve ubiquity. The current study investigates the perceived effect on driving style of a simple graphical-dashboard display depicting an animated coffee cup. This display incorporates associative mental models and contextual relevance to increase the salience of inefficient vehicle movements and nudge drivers to adopt smoother driving. An online Amazon-Mechanical-Turk survey (92 participants) revealed significant preference for the coffee-cup over a dial-gauge display when controlling for demographic variables. This result offers preliminary indication that a behavioral nudge may be effective in influencing drivers to adopt eco-driving practices.

Keywords: eco-driving, pro-environmental behavior, behavioral economics, nudge theory, cognitive ergonomics, regulatory focus theory

1 Introduction

This study takes an interdisciplinary approach to reduce vehicle energy consumption by applying theories from social and cognitive psychology to design display interfaces. The use phase often represents the largest portion of a product's environmental impact [1, 2]. While recent advances in electric vehicle (EV) technology reduce or eliminate tailpipe carbon emissions, EVs still generate substantial emissions at a systems level. In addition, these technological developments are slowed by the massive infrastructure cost and industry resistance associated with such transitions. Reducing use-phase energy consumption is as important for EVs, given their limited range, long charging times, and anticipated growth in vehicle sales. Thus, there is an immediate need for lower-barrier initiatives, even if these are only partial solutions.

A principal goal is plausible ubiquity, where a worthwhile proportion of the relevant population can reasonably be expected to adopt the proposed solution. Notably included are those who are not sufficiently motivated to make changes proactively. With this goal, the current study evaluates whether redesigning the dashboard energy-consumption display could influence drivers to adopt a more energy-efficient driving style. The proposed display, an animated cup of coffee, combines principles from behavioral economics and cognitive ergonomics to subtly influence driver behavior.

1.1 Eco-Driving. Eco-driving refers to practices undertaken by drivers to reduce vehicle energy use. Cumulatively, these practices represent significant value for resource conservation and climate-change reduction. Household and individual energy use accounts for 32–41% of total carbon emissions, and personal vehicles are the largest single contributor [3]. Sivak and Schoettle classified decisions as strategic (e.g. vehicle selection), tactical (e.g. route selection), and operational (e.g. driving speed) [4]. The strategic and tactical decisions that can most significantly conserve energy are vehicle selection and avoidance of traffic. However, both involve factors with greater variation between drivers and are often not fully within driver control, such as region of residence. The current work aims to address operational decisions since these are the 'lowest hanging fruit' in a behavioral intervention. The operational eco-driving techniques most commonly recommended are [3-5]:

(1) soft acceleration
(2) coasting to decelerate
(3) anticipatory driving to avoid sudden starts and stops
(4) consistent speeds
(5) avoiding high speeds
(6) low engine revolutions per minute (RPM)
(7) reduced idling

The first five of these techniques are equally relevant for EVs as for internal combustion (IC) vehicles. In fact, many of the more sophisticated efficiency displays are found in EVs due to limitations in range and recharging time. Techniques 1-4 are closely related and can be described as reducing acceleration, which includes both positive and negative changes in velocity. Technique 6 (low engine RPM) is independently controlled in manual transmission ICs, whose use is declining. In automatic transmissions, engine RPM is related to acceleration intensity. Techniques 5 (avoiding high speeds) and 7 (reducing idling) are distinct from vehicle acceleration. However, both involve additional contextual complexity, e.g., speed limits and safety for driving speed, weather conditions and auxiliary devices for idling.

1.2 A Simplified Eco-Driving Model. With so many eco-driving techniques directly related to reducing acceleration, a behavioral intervention is developed to reduce longitudinal acceleration variance. Acceleration variance represents a cumulative measure that accounts for both positive and negative changes in velocity. The more time a driver spends accelerating and the more intense those accelerations, the greater the resulting variance. We refer to a driving style characterized by low longitudinal acceleration variance as “smooth” and a driving style with high variance as "dynamic". While “aggressive” is commonly used to describe a high-acceleration driving style, we wished to avoid its emotional connotation, which is irrelevant to the current discussion.

Most currently used driving-efficiency displays show energy consumption either graphically or numerically. In ICs, this measure is usually in miles per gallon (MPG), gallons per 100 miles (gal/100mi), or liters per 100 kilometers (L/100km). While less precise than direct energy consumption, the use of acceleration as a measure of driving efficiency may be more intuitive and easier for drivers to operationalize. This is important, as lack of awareness of energy interactions is a key cause of energy overuse [6]. Further motivating the use of acceleration is that it can be measured in the negative direction (deceleration) as wasted kinetic energy. In contrast, energy consumption is only measured at the moment of use. Even for EVs with regenerative braking, maintaining kinetic energy will always outperform energy regeneration due to losses in energy conversions.

An important consideration is that the target behavior for drivers must be realistic. Safety is still the primary concern and high-intensity accelerations are often required to perform defensive or evasive maneuvers. In addition, route characteristics, such as grade profile (flat vs. hilly) and traffic patterns are often beyond drivers’ control but influence their acceleration behaviors.

1.3 Pro-Environmental Behavior Interventions. Steg & Vlek describe pro-environmental interventions as either informational or structural strategies [7]. Informational strategies aim to change perceptions, motivations, and knowledge, whereas structural strategies aim to change external factors such as policy and technology. Pro-environmental efforts have traditionally focused on these two approaches with limited success [8]. Structural strategies typically have high barriers to implementation. For policy changes, these often include political and corporate resistance. Technology developments often face high infrastructure costs and low market buy-in, such that business decisions can impede eco-conscious design [9]. Even in best-case-scenarios, structural changes have long timelines and high costs. Informational strategies are far easier to implement, but generally lead to increased knowledge without corresponding behavioral changes [10].

Outside this informational-structural dichotomy, other strategies exist. These include strategies that aim to influence behavior by adjusting incentive structures, employing cognitive biases, or eliciting emotional responses [11]. Such strategies are relatively unused in eliciting pro-environmental behavior and offer another opportunity for progress.

1.4 Nudge Theory. Psychological frameworks that regulate the effectiveness of interventions to elicit behavioral change may be applied to more substantially modify behavior. Several dual-process theories have examined the degree to which cognitive processing is controlled and deliberative, or automatic and reflexive [12-15]. Broadly speaking, cognitive operations are predominantly governed by one of these two processing systems. Reflexive processing is largely subconscious and relies on decision-making heuristics. In contrast, deliberative processing is conscious and used with awareness when, for example, carefully considering a decision or problem. Dual-process theories generally recognize that people are not perfectly rational actors and help explain why people consistently make suboptimal decisions in certain situations.

Informational strategies provide stimuli for the deliberative process in the hopes that new information will tip the balance toward a different decision. However, pro-environmental behaviors are often controlled by the reflexive system, where information does not have the opportunity to affect these behaviors. In these cases, interventions that influence reflexive decisions can be more effective. Such interventions have become popular in business and marketing where they are known as “nudges”. Thaler and Sunstein, who introduced the term, describe a nudge as something that “alters people’s behavior in a predictable way without forbidding any options” [16]. This approach aims to target reflexive processing by manipulating factors such as framing and salience in the choice architecture. Nudges show considerable promise as interventions for pro-environmental behavior, including in vehicles that provide feedback on driving patterns [17].

The above multidisciplinary literature informed the development of an eco-driving nudge that aims to be effective for a diversity of drivers. Beyond demographic factors, this diversity includes differences in driving experience and frequency, existing driving styles, and attitudes toward energy efficiency and the environment. The intervention designs outlined in the next section aim to fulfill these needs.

2 Intervention Design

As established in Section 1.2, most operational eco-driving recommendations can be summarized as reduced variance in vehicle acceleration. The following two conditions guided the initial development of a nudge to reduce acceleration variance. First, the intervention should make no association with the environment and energy efficiency. Second, the intervention should not be so intrusive as to distract from the driving task nor prompt users to deactivate or remove it.

The first condition is intended to address drivers' varying inclinations toward efficient driving. Even people who are eager to be energy efficient may face an intention-action gap, where their attitude does not lead to corresponding behaviors [18]. For example, social-desirability bias can lead to statements of good intention that are later sidelined to avoid compromises that frequently accompany pro-environmental behaviors. Various strategies aim to overcome this gap [19-22], but risk worsening adoption in people with neutral-to-averse attitudes toward environmental efforts. Such people, with perhaps the most potential for improvement, may dismiss or respond negatively to interventions communicated as pro-environmental. Thus, an intervention display was developed that does not reference the environment.

The second condition, that the display be minimally intrusive and distracting, is primarily a safety requirement, given the consequences of taking drivers' attention from the roadway even briefly [23]. Nudges are also intended to be perceived as voluntary due to people's aversion to feeling controlled. Greater imposition often leads to lower intrinsic motivation and increased resistance toward the behavior [24].

Under these conditions, an animated dashboard display was conceived that depicts the cross-section of a full cup of coffee which responds to vehicle-acceleration data. That is, the coffee would realistically slosh right and left in the cup in relation to forward and backward movements of the vehicle. If the movements become too intense, the coffee would spill over the lip of the cup.

This intervention concept meets the first condition by not having any relation to the environment. Rather, aversion to spilling is simply a subtle game of avoiding a simulated mess. Fulfilling the second condition depends in part on the details of the actual in-vehicle implementation to ensure that the display does not cause distraction that would degrade safety. The developed intervention does not prevent drivers from accelerating with high intensity, but only dissuades this behavior with intangible consequences.

2.1 Associative and Contextual Elements. The animated coffee-cup display is hypothesized to be an effective nudge due to a combination of what we have termed *associative* and *contextual* elements. The *associative* element refers to depicting, in a display interface, accurate real-life physical scenarios. For example, driving displays that depict realistic movement of in-vehicle objects or the vehicle on the road are associative. In the coffee-cup display, the full cup of coffee would slosh and spill in response to corresponding vehicle accelerations. The *contextual* element refers to depicting in a display interface, stimuli relevant to an activity. For example, the depiction of dashboard instruments, vehicle components, or passing scenery are contextually relevant to driving. Drinking a beverage is a relatively natural and common task while driving [25]. Thus, in the coffee-cup display, a cup of coffee in a cup holder is expected to be a familiar and relatable scenario, even for people who don't drink coffee.

By combining these elements, the expectation is that drivers will have a visceral response to the possibility of spilling even a simulated cup of coffee. This intuitive mental model facilitates a transition to a driving style people might adopt if they had a real open cup of coffee in their vehicle. This targeted driving style is likely to be very similar to a purposeful low-acceleration-variance driving style. While high-acceleration maneuvers may be required for safety, the lack of real consequence from an animated display should allow safety to take precedence when necessary.

For comparison, two additional displays were conceived that constitute the associative element without the contextual one and vice versa. An animated wrecking ball, hung between two walls, would respond to changes in vehicle acceleration by swinging and striking the walls, cracking them. The wrecking-ball display is associative as it represents the physics of a real wrecking ball, which would cause genuine damage. However, the contextual element is absent, since a wrecking ball is foreign to the context of driving a car. The third display is a dial gauge, similar to traditional speedometers or tachometers, and shows the current acceleration and its directionality. The dial gauge is contextually relevant, resembling displays often found in vehicles, but lacks the associative element, in not representing a real-world physical scenario with inherent consequences.

Of note, each display, the dial gauge, wrecking ball, and coffee cup (see Fig. 1), are merely examples of displays that are contextual, associative, and with both elements combined. Specific display concepts were required for the purposes of testing, but any specific display design that is developed for testing has inherent limitations in generalizability.

2.2 Regulatory Fit. A widely accepted social-psychology theory with relevant implications here is Regulatory Focus Theory (RFT) and its associated regulatory fit effect [26, 27]. RFT proposes that people pursue goals from either a promotion orientation, i.e., the pursuit of maximal gains, or a prevention orientation, i.e., the pursuit of minimal losses. Achieving a fit between framing a goal as a loss or a gain and a person's regulatory focus has been found to increase both motivation towards the goal and success in achieving it. While regulatory focus is a relatively stable aspect of personality, a specific orientation can be primed by situational context. Given the prominent safety considerations involved in driving, it is possible that people on average adopt a prevention orientation and avoid hazards while driving. In this case, a driving-behavior intervention that is framed toward prevention could be more influential than one framed toward promotion. All three displays have such a prevention framing since the goal is to avoid spilling the coffee, hitting the wall, and having the gauge needle enter the red zone. Additionally, the prevention framing of these displays might itself prime prevention orientation in drivers and make them more safety conscious. Thus, prevention orientation for safe driving and eco-driving may be complementary.

2.3 Incorporating Ergonomic Design Principles. Recent academic literature on displays aim to promote greater adoption of eco-driving practices [28-31]. Car manufacturers have also begun expanding their developments in this direction, moving beyond simple fuel-consumption displays into more elaborate graphical ones. These displays vary on intuitiveness and effectiveness, but many do poorly when considered from the perspective of established design principles. Within the field of cognitive ergonomics, displays ought to be designed to optimize usability. Principles outlined in this field were developed by considering the cognitive characteristics of attention, perception, memory, and mental models [32]. Their implementation has offered profound improvements in a variety of applications, especially high-risk environments such as aviation and industrial facilities.

These design principles were applied in developing the three intervention displays to be evaluated, as drivers should be able to understand the displays without any instruction or training.

An effective display must interact with driver attention appropriately. An efficiency display that is incorporated into a dashboard interface must be salient enough to be an effective reminder, while not being distracting. Movement and color are helpful for increasing salience, the former being inherently part of the coffee-cup and wrecking-ball displays. While using movement to increase salience could also increase distraction, cognitive-processing ease and moderate movement rates can help maintain low visual fixation times during use. All proposed displays use color to improve threshold detection by providing redundancy. Three colors, green, yellow, and red were chosen for their well-understood relation to 'good/go', 'warning/slow down', and 'bad/stop'. No additional information is shown that competes for attention.

One aspect of the coffee-cup and wrecking-ball displays involved a compromise between multiple display-ergonomics guidelines. These displays depict longitudinal (forward and backward) accelerations using side-to-side motion of an element in a two-dimensional (2D) display. This movement mapping is not the most compatible, but was chosen to maintain very simple depictions. A fully compatible mapping of vehicle motion to display motion would require three-dimensional (3D) depictions of the coffee cup and wrecking ball. The significantly increased display complexity may interfere with ease of processing the displayed information. St. John et al. compared comprehension of 2D and 3D displays and found relative position judgements to be more accurate in 2D displays [33]. While the mapping incompatibility may confuse some new users, the relationship is expected to very quickly become apparent once in use.

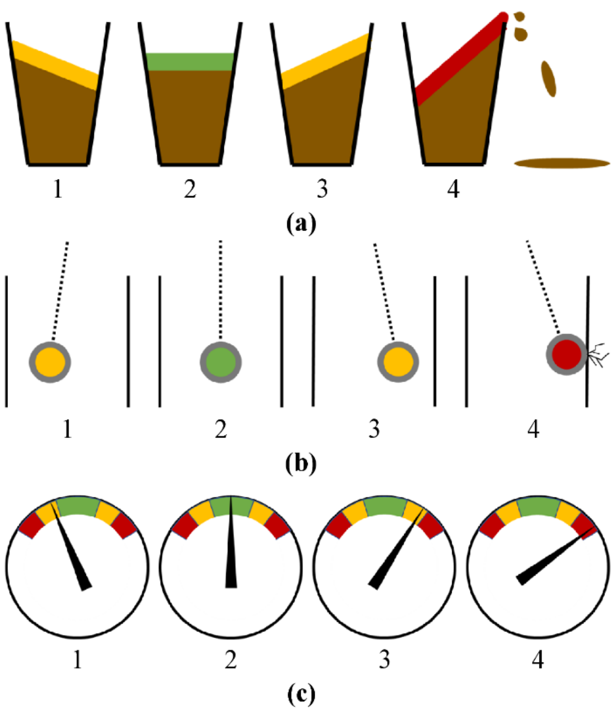

Fig. 1 Frames of coffee-cup (a), wrecking-ball (b), and dial-gauge (c) displays, corresponding to 1) moderate braking, 2) constant speed, 3) moderate acceleration, and 4) hard acceleration.

The dial-gauge display has the advantage of familiarity since it resembles common dashboard displays. This similarity can also be a limitation by making the display correspondingly less salient. A possible benefit of depicting a physics analogy is that once drivers internalize the physical feelings that correspond to certain display states, they can predict the displays' behavior. The three intervention displays were mocked-up for evaluation as four sample frames of the intended animated concepts, shown in Fig. 1.

3 Methods

An online survey was conducted with the aim to measure each display's perceived effectiveness across a series of driver subgroups. These subgroups differentiated drivers by seven demographic and driving-related measures. The 92 responses were sufficient to maintain a 5% Type I error rate and 80% power to detect effects of size d = 0.3. This effect size lies between the small (0.2) and medium (0.5) effect thresholds suggested by Cohen [34]. The survey is similar in structure to the eco-driving survey conducted by McIlroy & Stanton [35]. The present work is a preliminary evaluation of the displays' self-reported effectiveness and is intended to answer the following research questions:

RQ1: Is the coffee-cup display perceived to be more effective than the wrecking-ball and dial-gauge displays when controlling for all of the following variables?

- driver age and gender
- driving experience and frequency
- driving style (smooth/dynamic)
- driver inclination toward efficient driving (eager/averse)
- use of a vehicle with an existing efficiency display

RQ2: Among drivers whose primary vehicle has an existing efficiency display, is the perception of each intervention display's effectiveness different when comparing to the existing display?

3.1 Survey Platform. The survey was offered on Amazon Mechanical Turk (MTurk), a crowd-sourcing platform of anonymous workers who complete tasks online for modest financial compensation. MTurk worker demographics have been found to be diverse, but not exactly representative of the general population in the United States, where over half of workers reside [36]. While a popular source of data for social-science research, MTurk worker education, employment, and income levels suggest a more educated, but underemployed population. Task visibility was restricted to the United States and Canada since international diversity of the MTurk worker pool is too sporadic to appropriately account for regional effects. The survey was identified only as a "Survey on Driving Style" to avoid revealing the study's true nature. Approved workers were paid $0.50 USD for finishing the survey, and average completion time was 7.5 minutes. An attention-check question was included in the survey to remove the results of inattentive workers.

3.2 Survey Design. The survey comprised of the following five sequential sections:

(1) Screening and demographics
(2) Driving style
(3) Intervention displays
(4) Existing display
(5) Driver inclination toward efficient driving

The questions were phrased and ordered so as to postpone hinting at the study's objective, which may bias responses to remaining questions. No explicit mention of energy efficiency was made until section 4 and no mention of the environment until section 5. Most of the questions used some variation of a Likert scale. All but one question (discussed below) used a six-point scale to force participants to choose at least a slightly directional response and avoid large numbers of neutral responses. Question order was randomized within the driving style (2) and driver inclination (5) questionnaires, as was the order that the three intervention displays were presented. In addition, all questions were mandatory such that participants could not continue without answering.

3.2.1 Screening and Demographics. Screening questions selected for participants who self-reported the following: 1) held a valid full or intermediate / provisional driver's license, 2) had at least two years of driving experience, and 3) had driven at least once per week during the last six months. These criteria selected for routine drivers who were more likely to possess consistent driving habits. These questions also provided data on driver demographics and were followed by questions on age and gender (Appendix, Q2-Q6).

3.2.2 Driving Style. The next survey section assessed participants' driving style on the "smooth" to "dynamic" scale described in Section 1.2. As the first of two parts, a questionnaire asked participants to indicate how accurately ten statements described them (Appendix, Q7). Responses were collected using the following six-point Likert scale: 1) Not at all, 2) Slightly well, 3) Somewhat well, 4) Moderately well, 5) Very well, and 6) Extremely well. Questionnaire statements included: I accelerate out of intersections faster than other vehicles; My driving style would be more accurately called 'sporty' than 'relaxed'; and Loose items in my car often shift backward and forward as I drive. All statements were worded in the same direction, i.e., responding with 6 (Extremely well) always corresponded with a more dynamic driving style. Reverse wording was avoided to reduce misinterpretation of questions, which often results in the emergence of a separate unintended factor [37].

Next, participants were presented with a looping animated video that showed two cars, X and Y, driving between two stop signs, one car at a time (Fig. 2). Participants were asked to indicate which car more accurately reflected their own driving style (Appendix, Q8). Car X accelerated and braked harshly, with moderately noticeable car tilting, and completed the road segment in 8 seconds. Car Y accelerated and braked gently and evenly, completing the segment in 12 seconds. Responses were made with a six-point slider that ranged from Car X at one extreme to Car Y at the other. Participants were not allowed to proceed until the 20-second animation had completed one full loop. The next question aimed to confirm participant understanding that Car X's style would be referred to as "dynamic" and Car Y's style as "smooth". These terms were important points of reference for answering subsequent intervention questions.

3.2.3 Intervention Displays. Three intervention displays, shown in Fig. 1, were presented to participants simultaneously on one page, but in random sequence. The question briefly explained that each display showed four sample frames of an animated display that would respond to the vehicle's forward-backward motion (Appendix, Q11). Participants were then asked to indicate, for each display, how effectively it would influence them to drive more smoothly or dynamically than they typically do. Responses were made using the following seven-point Likert scale: 1) Very 2) Moderately 3) Slightly effective for driving more smoothly, 4) No effect, and 5) Slightly 6) Moderately 7) Very effective for driving more dynamically. By giving participants freedom to choose the direction of influence, the question avoided hinting at the study's objective or eliciting a socially desirable response. Note that each display was evaluated independently, not ranked.

3.2.4 Existing Display. Participants were then asked whether the vehicle they typically drove had an existing efficiency display. Those who answered in the affirmative were presented with additional questions as follows (Appendix, Q14-17) that were analyzed as part of RQ2. First, participants were asked to indicate how effective their existing display was in influencing them to drive more efficiently. Next, they were shown the same intervention displays as before. Participants were asked to indicate, relative to their existing display, how effective each display would be in influencing them to drive more efficiently. Note that, different from the first intervention-display question, this question 1) was asked in relation to the driver's existing display, and 2) asked about efficient driving instead of smooth vs. dynamic driving. This is because "efficiency" had not yet been mentioned when the first version of the question was asked, but it was necessarily revealed when referring to an existing display.

3.2.5 Driver Inclination toward Efficient Driving. The final survey section was a six-item questionnaire (Appendix, Q18). This questionnaire was intended to assess participants' propensity for efficient driving, which we call *driver inclination* on a scale from *averse* to *eager*. Participants were again asked to indicate how accurately six statements described them on the same six-point Likert scale from 1) Not at all to 6) Extremely well. Questionnaire statements included: I would be willing to drive more smoothly than I do now; Environmental sustainability and preventing climate change are important to me; and I believe efficient driving is a worthwhile way to reduce environmental impacts. All statements were again worded in a consistent direction, where 6 (Extremely well) corresponded to an eager inclination.

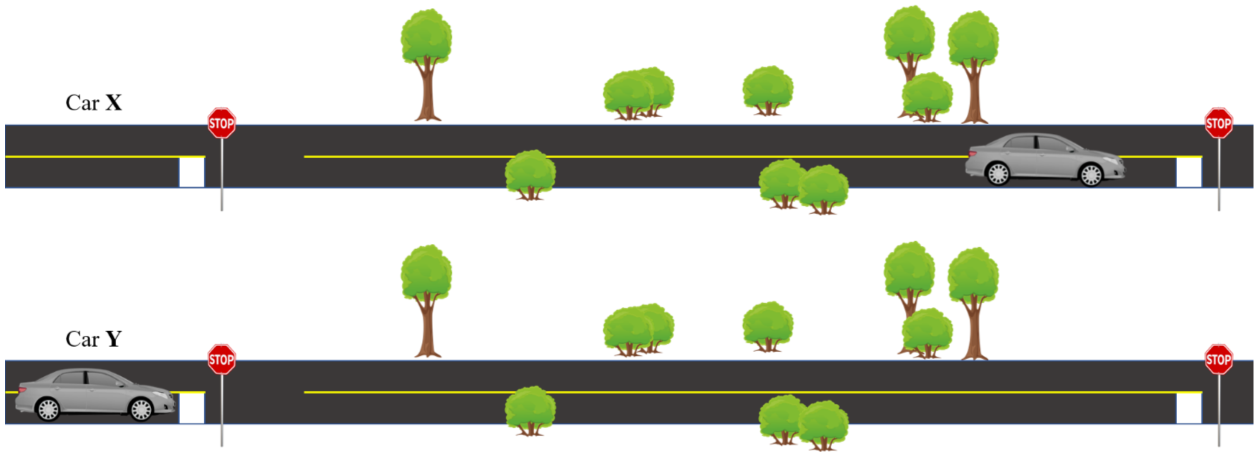

Fig. 2 A single frame of the driving-style animation where Car X displayed the harsh movements of a "dynamic" style and Car Y the gentle movements of a "smooth" style.

4 Results

MTurk survey responses were collected in February 2019. Responses of six participants who completed the survey in under 3 minutes (180 sec) were removed. These durations were outliers, and the corresponding responses were deemed insufficiently carefully considered. This resulted in a final sample size of 92 (42 female, 50 male) participants.

4.1 Participant Demographics. Two participants had an intermediate/provisional license, and the rest had a full license. Regarding driving experience, 27 participants had 2-10 years while the remaining 65 had 10 or more years. Regarding an existing efficiency display, 38 participants indicated that the vehicle they typically drove had one, while the remaining 54 did not have one. The distributions of participants' age and driving frequency are shown in Fig. 3 and Fig. 4. Notably, 23 participants indicated that they usually drive four or more hours per day. These people likely drive for work, e.g., for delivery or taxi/rideshare companies.

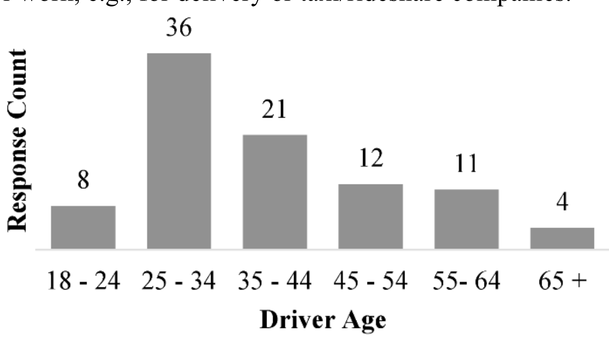

Fig. 3 Distribution of participants' ages

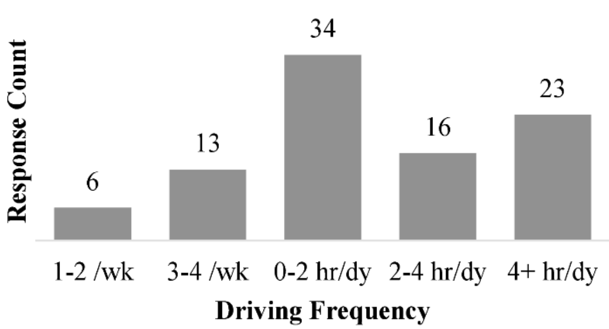

Fig. 4 Distribution of participants' driving frequency

4.2 Measurement of Driving Style. All scores from the driving-style questionnaire (Appendix, Q7) were reversed such that high scores reflected a smooth driving style. A Principal Components Analysis (PCA) was then performed on all the questionnaire items as well as the question based on the video shown in Fig. 2 (Appendix, Q8). A scree plot suggested the extraction of a single factor, which matched the questionnaire's objective to measure a single dimension of driving style from dynamic to smooth. Only items with PCA loadings above 0.4 were retained for scoring the factor, which eliminated two items (Appendix, Q7.8, Q8). That is, these two items did not accurately measure the same underlying construct as the other items. The final extracted factor with 9 questionnaire items explained 60% of the variance, had high model fit at 0.98, and very high reliability with Cronbach's α=0.91. A significant Bartlett's test meant correlations between items were sufficiently large for PCA, $\chi^2(36)=505$, $p<0.001$. The correlation-matrix determinant (det=.003) indicated no excess multicollinearity. Residuals were within acceptable limits.

The PCA generated a single standardized score for each participant, which represents the participant's relation to the dynamic-smooth factor. Positive scores pointed to a smoother driving style and negative scores a more dynamic style. A score near zero signified that the participant's responses to the questionnaire items were close to the mean.

4.3 Measurement of Driver Inclination Toward Efficient Driving. Another PCA was similarly performed on the driver-inclination questionnaire (Appendix, Q18). Responses were analyzed as reported, where high scores reflected an eager inclination. A scree plot suggested two possible inflection points extracting either a single factor or three. A single factor was extracted for two reasons. First, only one eigenvalue exceeded 1, which follows the commonly used Kaiser criterion to drop factors with eigenvalues less than 1. Second, the objective of the questionnaire was to measure inclination toward efficient driving as a single dimension from averse to eager. All items had loadings above 0.4 and were thus retained for scoring the factor. The final model explained 58% of variance, had high model fit at 0.94, and high reliability with Cronbach's α=0.85. Bartlett's test was significant, meaning that correlations between items were sufficiently large, $\chi^2(15)=252$, $p<0.001$. The correlation-matrix determinant (det=0.057) indicated no excess multicollinearity. There was a high proportion of large residuals, suggesting that additional factors could have been extracted to improve model fit. The PCA generated standardized scores for each participant, which represented the participant's relation to the averse-eager factor. Positive scores pointed to a more eager inclination toward efficient driving, negative scores a more averse inclination, and scores near zero were close to the mean.

4.4 RQ1: Perceived Effectiveness of Displays. The first research question concerned whether the coffee-cup display is perceived as more effective than the wrecking-ball and dial-gauge displays when controlling for various demographics. A linear mixed-effects model was used to analyze the different display types' perceived effectiveness on influencing participants' driving style. Since each participant scored all three displays, display type was a within-subjects variable with participants modeled as a random factor to account for individual variability. All other measures were included as between-subject fixed-effect covariates to determine whether any effect of display type existed when controlling for these other fixed variables. These included categorical variables: age, gender, driving experience, driving frequency, existing display, and continuous variables: driving style and driver inclination as standardized factor scores from the PCAs.

4.4.1 Variable Manipulation. Some of the categorical control-variable levels had very small group sizes. For example, age was recorded on a six-level scale, but the 18-24 and 65+ groups had only eight and four participants, respectively. Therefore, some levels had to be merged, otherwise sample-size limitations would have made estimation non-robust. The merging of levels was guided by sample distributions and practical perspectives with the final binary groupings presented in Table 1. From a practical perspective, crash rates have been found to drop dramatically with driver age in a roughly logarithmic decay until ages of at least 60-70 years [38]. For the age distribution in our study, most of that decrease in crash risk occurs up to approximately 35 years of age. Thus, 35 years was chosen as the split point for a binary age variable. Regarding driving frequency, those who reported driving an average of two or more hours per day are likely to include professional and other high-volume and habituated drivers. This is a group which often consumes lower attentional resources while driving [39]. Thus, two or more hours per day was chosen as the split point for a binary driving frequency variable.

Table 1 Binary categorical demographic variables for RQ1 following group merging to avoid small sample sizes

Variable	Level 0	Level 1
Age	<35 years (n = 44)	≥35 years (n = 48)
Gender	Female (n = 42)	Male (n = 50)
Driving experience	<10 years (n = 27)	≥10 years (n = 65)
Driving frequency	<2 hrs/day (n = 53)	≥2 hrs/day (n = 39)
Existing display	No display (n = 54)	Has display (n = 38)

The dependent variable, perceived effectiveness of the display, was reported on a seven-point Likert scale. Recall this scale ranged from 1) Very effective for driving more smoothly, to 7) Very effective for driving more dynamically, with 4) No effect, in the middle. The responses were centered such that "No effect" scored 0, "Very effective" toward smooth scored 3, and "very effective" toward dynamic scored -3. Thus, a positive perceived effectiveness corresponded to effectiveness toward smoother driving.

4.4.2 Model Construction. Of primary interest is whether the main effect of display type was significant while controlling for the effects of all other variables. An additional exploratory analysis looked at the two-way interactions of these covariates with display type. However, the sample was neither sufficiently large nor complete enough to examine all possible interactions at an adequate power level. Building the mixed-effects model progressively, significant variance was accounted for in both random intercepts across participants and random slopes for display type, so both were included in the model. All covariates and their two-way interactions with display type were entered in the model in a single block. Next, a both-ways stepwise regression was performed to build the final model by minimizing the AIC (Akaike Information Criterion). The resulting model included only display type, driving frequency, and the interaction between the two as predictors, meaning that no other covariates had a significant effect on the model.

4.4.3 Model Results. Fig. 5 shows the adjusted mean scores for each display type's perceived effectiveness with 95% error bars. All mean scores are positive, indicating that participants predominantly felt that all the displays would influence them to drive more smoothly. The final stepwise reduced model is presented in Table 2 and adjusted means are reported below.

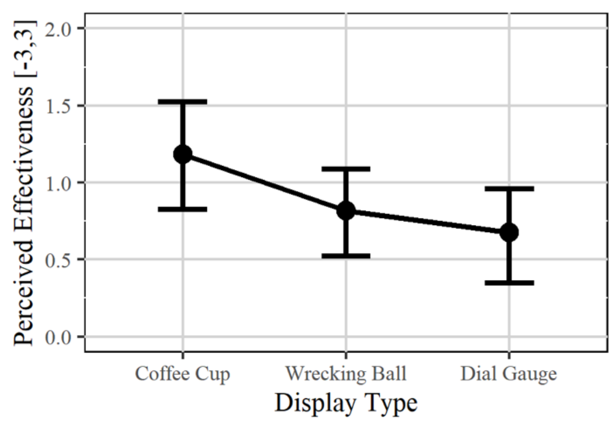

Fig. 5 Mean perceived effectiveness (bounds: -3, 3) by display type with 95% error bars. Perceived effectiveness of the coffee-cup display is significantly higher than the dial-gauge display, but not significantly higher than the wrecking-ball display.

Table 2 Linear mixed-effects model of intervention displays' perceived effectiveness while controlling for driving frequency

	b	*SE*	*DF*	*t*	*p*
(Intercept)	1.12	0.18	180	6.25	<.001
Cup vs Ball	-0.32	0.18	180	-1.80	.073
Cup vs Dial	-0.45	0.21	180	-2.21	.028*
Driving frequency	0.41	0.18	90	2.26	.027*
Cup vs Ball : Frequency	-0.32	0.18	180	-1.80	.073
Cup vs Dial : Frequency	-0.38	0.21	180	-1.84	.068

* p < .05

The main effect contrast between the coffee-cup display (M=1.12, SE=0.18) and the dial-gauge display (M=0.67, SE=0.16) was significant, b=-0.45, t(180)=-2.21, p<.05, d=0.47. However, the main effect contrast between the coffee-cup display and the wrecking-ball display (M=0.80, SE=0.15) was not significant, b=-0.32, t(180)=-1.80, ns. Only one other covariate, driving frequency, was retained in the model and had a significant main effect on the perceived effectiveness of the displays, b=0.41, t(90)=2.26, p<0.05, d=0.34. Participants who drove less than two hours per day perceived the displays as more effective overall in influencing a smoother driving style than those who drove two hours or more per day. Fig. 6 shows the interaction between display type and driving frequency; however, only the main effect of frequency was significant and not the interaction.

When the model was constructed using forced entry including all covariates and two-way interactions with display type, the significance of all covariates was unchanged. An examination of model assumptions revealed acceptable normality and homoscedasticity of residuals and no excess multicollinearity.

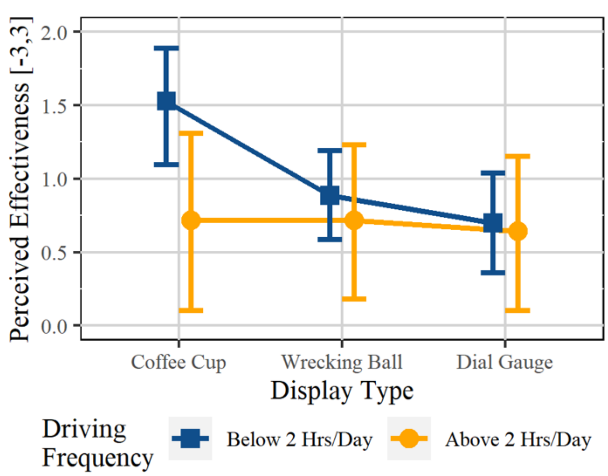

Fig. 6 Mean perceived effectiveness (bounds: -3, 3) by display type and driving frequency with 95% error bars. Significant main effect of driving frequency but no significant interaction with display type.

4.5 RQ2: Relative Effectiveness of Displays. The second research question was specific to participants reporting an existing efficiency display in their current primary vehicle: Do these drivers perceive each intervention display's effectiveness differently when asked to compare it to their existing display? To answer this question, two additional linear mixed-effects models were used to analyze these 38 participants. Both models included display type as a within-subjects variable with participant modeled as a random factor to account for individual variability. The subgroup of participants who reported having an existing display were first asked how effective they felt their existing display was at influencing them to drive more efficiently. This perceived effectiveness of their existing display, and its interaction with display type, were included as between-subject fixed-effect covariates in both models. The first model describes absolute effectiveness in terms of smoothness. This model examines whether intervention displays (coffee-cup, wrecking-ball, and dial-gauge) were perceived to be effective for influencing smoother driving when controlling for existing display effectiveness. The second model describes relative effectiveness in terms of efficiency. This model examines whether participants perceived the intervention displays as relatively more or less effective than their existing display in influencing them to drive more efficiently, when controlling for existing display effectiveness. In the absolute model, participants' ratings of the intervention displays were made as independent evaluations, while in the relative model, ratings were made as comparisons to their existing display. Further, the effectiveness ratings in the absolute model were in terms of influencing smooth driving style, while in the relative model they were in terms of influencing efficient driving.

4.5.1 Variable Manipulation. The existing display's effectiveness was reported on a six-point Likert scale from 1) Not effective at all, to 6) Extremely effective. Due to a low number of responses at some levels, the scale was grouped into two categories: "Lower effectiveness" including 4) Moderately effective and below (n = 22) and "Higher effectiveness" including 5) Very effective and above (n = 16).

The dependent variable for the absolute model was the same as in RQ1 and was scored equivalently. The dependent variable for the relative model was the effectiveness of each intervention display when compared to the existing display. This measure was reported on a six-point Likert scale from 1) Much less effective, to 6) Much more effective than the existing display at influencing more efficient driving. Since there was no neutral option, 0 was set between the two middle options such that the extremes were scored 2.5 for being much more effective and -2.5 for being much less effective. Thus, a positive relative effectiveness corresponded to a greater perceived effect of the intervention display over the existing display.

4.5.2 Absolute Effectiveness in Terms of Smoothness. Similar to the RQ1 analysis, the dependent variable here is the perceived effectiveness of intervention displays on influencing driving style. Building the mixed-effects model progressively, significant variance was accounted for in random intercepts across participants, but not random slopes for display type, so only random intercepts were retained in the model. Both covariates and their interaction term were entered in a single block of the regression. The coffee-cup display (M=0.96, SE=0.27) scored higher than both the wrecking ball (M=0.66, SE=0.27, b=-0.29, t(72)=-0.95, ns) and the dial gauge (M=0.71, SE=0.27, b=-0.24, t(72)=-0.78, ns). Participants with an existing efficiency display appeared to have a slight preference for the coffee-cup display, as shown in Fig. 7, but the difference was not significant. There was also no interaction between display types and the effectiveness of the driver's existing display, and no main effect of the existing display's effectiveness.

The model showed some evidence of non-normality and heteroscedasticity of residuals, likely due to the small sample size, but there was no significant multicollinearity.

4.5.3 Relative Effectiveness in Terms of Efficiency. Drivers who reported that they had an existing display were asked to consider each intervention display again. This time, participants reported the effectiveness of the intervention displays relative to their existing display for influencing them to drive more efficiently. A linear mixed-effects model with the same subgroup of participants was run with the same covariates, but with relative effectiveness as the dependent variable. For this model, display type, existing-display effectiveness, and their interaction were again entered in the model in a single block. There was significant variance in random intercepts across participants, but not in random slopes for display type, so only random intercepts were retained in the model.

Once again, no significant effects were found. However, a different trend in scoring between display types as shown in Fig. 8 revealed that scores for the coffee-cup display (M=0.00, SE=0.27) might be higher than for the wrecking-ball display (M=-0.25, SE=0.22, b=-0.25, t(72)=-0.91, ns), but lower than for the dial-gauge display (M=0.50, SE=0.23, b=0.49, t(72)=1.43, ns). More data is required to assess whether these trends are robust. There was no interaction between display type and existing-display effectiveness and no main effect of the existing display's effectiveness. The model had acceptable normality and homoscedasticity of residuals and no excess multicollinearity.

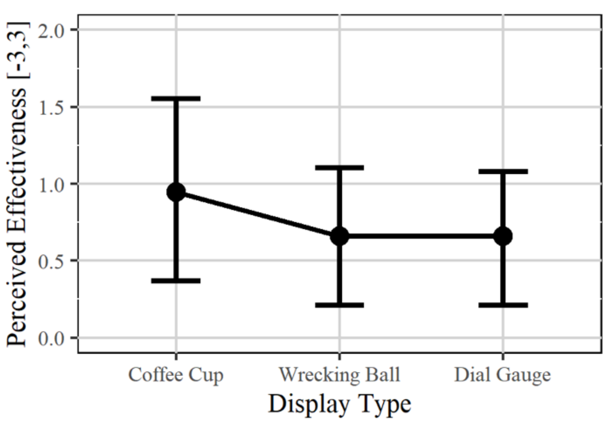

Fig. 7 Mean absolute effectiveness (bounds: -3, 3) by display type for drivers with an existing display with 95% error bars. The coffee-cup display scored higher on effectiveness than the other two displays, but not significantly.

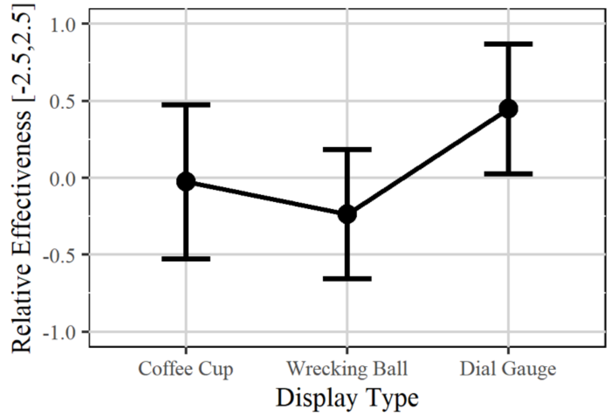

Fig. 8 Mean relative effectiveness (bounds: -2.5, 2.5) by display type compared to drivers' existing display with 95% error bars. The dial-gauge display scored higher on effectiveness than the other two displays, but not significantly.

5 Discussion

This survey was a preliminary investigation into the effectiveness of the coffee-cup display as an eco-driving nudge. Results reveal how influential the tested intervention displays could be for promoting a smoother driving style, with reduced acceleration variance and lower energy consumption.

5.1 RQ1: Perceived Effectiveness of Displays. The first research question was whether the coffee-cup display was perceived to be more effective overall than the wrecking-ball and dial-gauge displays at influencing participants to drive more smoothly. The coffee-cup display scored significantly higher on perceived effectiveness than the dial-gauge, and higher, but not significantly, than the wrecking-ball. The complete forced-entry model attempted to control for: driver age and gender; driving experience, frequency, and style; driver inclination; existing display; and two-way interactions between these covariates and display type. The elimination during AIC stepwise reduction of all predictors except display type, driving frequency, and their interaction, indicated that none of the other covariates accounted for significant variance in the model. The significant difference in perceived effectiveness between the coffee-cup and dial-gauge displays in both forced-entry and final models suggests that the coffee-cup display might be preferred across demographic factors. However, the merging of covariate levels limits the robustness of the findings. In addition, the analysis showed that none of the two-way interactions with display type were significant, suggesting that differences between displays were not moderated by the other variables. The investigation of interactions was performed as an exploratory analysis without an a-priori hypothesis. A sample size sufficient to detect hypothesized main effects may be insufficient to detect interaction effects. Of interest, the difference in perceived effectiveness of the coffee-cup and dial-gauge displays was significant after controlling for driving style (dynamic to smooth) and driver inclination towards efficient driving (eager to averse). This suggests that the coffee-cup display may be effective for drivers of varying styles and environmental attitudes, which is a specific intention of this display design. However, this interpretation should be treated cautiously due to the study's small sample size, which may not have captured enough data to demonstrate this finding.

Participants who drive less than two hours per day perceived a significantly higher overall effectiveness for all displays than those who drive more than two hours per day. This could be because those who spend a large amount of time driving, possibly because they drive as their job, have more deeply ingrained driving habits that they don't feel a novel display would change. Of interest is whether this distinction would hold in a future study that takes direct measures of effectiveness instead of self-reported effectiveness.

Preference for the coffee-cup over the dial-gauge display, shown in Fig. 5, had a medium effect size (d = 0.47), which is an encouraging finding. The coffee-cup display being perceived as more effective than the much more familiar looking dial-gauge display is notable. The significant result in favor of the coffee-cup display suggests that the associative element may be an important and compelling aspect of the nudge. Further study is required to determine whether the combination of associative and contextual elements is more effective than either element alone, as hypothesized. The advantage of targeting regulatory fit in the goals presented by the displays could not be tested in this study. Subsequent studies that consider regulatory fit would benefit from developing a promotion-oriented display for comparison.

5.2 RQ2: Relative Effectiveness of Displays. The second research question asked whether drivers with an existing display perceived the interventions' effectiveness differently when comparing each to their existing display. The first model examined absolute display effectiveness in influencing driver style, while the second examined relative display effectiveness in influencing efficient driving. Both models controlled for existing-display effectiveness, since perceptions of new displays were likely to be influenced by existing-display experiences.

No significant differences were found between display types, but interesting trends in the means are worth further consideration. When the displays were rated on absolute effectiveness, before mention of fuel/energy efficiency, the coffee-cup display seemed to be preferred over the other two displays. A different trend arose when comparing each display's perceived effectiveness to influence more efficient driving with participants' existing displays. Here, the dial-gauge display scored higher and was the only display with a positive adjusted mean score. The coffee-cup display was second with an adjusted mean score of 0, and the wrecking-ball had the only negative adjusted mean effectiveness score.

The difference in results may be due to the framing of each question or the context in which they were asked, revealing potential bias toward the status quo. The absolute versus relative framing, and reference to influencing driving style versus more efficient driving, both changed between questions. In addition, comparing to an existing efficiency display may prime thoughts of energy efficiency which were absent in the first question, leading to different preferences. The relative-effectiveness question may have also introduced bias by referencing the existing display immediately after a question on its perceived effectiveness. Thus, familiarity of the dial-gauge display may have become a greater factor in participants' responses. Finally, the small subgroup sample size of 38 may have led to unrepresentative results.

5.3 Limitations of Self-Reporting. Generalizing the findings of this study raises several questions. Most fundamentally, participants self-reported the perceived effectiveness of interventions, and perceived effectiveness does not necessarily reflect actual effectiveness [40]. Furthermore, nudge interventions that employ reflexive-processing heuristics often influence users more than they would expect [16].

Another source of uncertainty is gauging how consistent participants' interpretations of the displays, questions, and response scales were with researchers' intentions. Since participants were shown very basic mock-ups of proposed displays, it is unclear how closely their understanding matched the displays' intended functionality. A study that exposes drivers to functional displays and measures driving style quantitatively using acceleration data is planned to offer more compelling results. Finally, MTurk data quality and representativeness could be questioned. Despite these limitations, the significant results suggest there is utility in further investigating the coffee-cup display and others like it. This study accomplished its purpose to gain preliminary insight into the coffee-cup display's potential to increase adoption of eco-driving practices.

6 Conclusion and Future Work

An animated coffee-cup dashboard display of instantaneous acceleration was perceived to be significantly more effective than a dial-gauge display among a variety of drivers (d=0.47). Preference for the coffee-cup over the dial-gauge display was not predicted by any measured demographic variables (age, gender, driving experience / frequency, driver style / inclination, existing display), and was significant after controlling for those variables. Frequent driving (two or more hours / day) predicted a lower overall perceived effectiveness of the intervention displays to influence driving style.

This study is an initial step and proof-of-concept to evaluate the effectiveness of an eco-driving nudge. The findings offer an encouraging indication that an ergonomically designed nudge intervention can effectively increase adoption of high impact eco-driving practices. A larger sample size would allow further investigation of interaction effects and relative effectiveness. Yet the question remains whether real reductions in acceleration variance and energy consumption would be found if drivers used the proposed displays in practice. Far greater inferences could be made from a study conducted on a driving simulator or instrumented vehicle. Each display could be developed into a functional prototype that responds to vehicle motion and presented in a realistic driving scenario. Effectiveness could then be determined objectively by measuring the variance of vehicle acceleration and cumulative energy consumption. A deeper study of the distraction potential of the displays would also be vital in such a study. Future research should also include other displays that incorporate the associative and contextual elements, individually and combined, to determine more generally whether these elements facilitate the nudge effect.

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Nomenclature

Associative Element = The depiction, in a display interface, of accurate real-life physical scenarios. For example, driving displays that depict realistic movement of in-vehicle objects or the vehicle on the road are associative.

Contextual Element = The depiction, in a display interface, of stimuli relevant to an activity. For example, displays that depict dashboard instruments, vehicle components, or passing scenery are contextually relevant to driving.

Smooth Driving Style = A driving style characterized by low longitudinal acceleration variance of the vehicle

Dynamic Driving Style = A driving style characterized by high longitudinal acceleration variance of the vehicle

Eager Driver Inclination = A driver who is willing to adopt a smoother driving style

Averse Driver Inclination = A driver who is resistant to adopt a smoother driving style

Appendix: Survey on Driving Style

The survey was constructed using Qualtrics, but it has been reproduced here for reference. Explanatory annotations that were not present in the survey are included in square brackets.

Q1: Please enter your MTurk Worker ID.

Q2: Do you hold a valid driver's license?
● Full license; ● Learner's permit; ● Intermediate/provisional license; ● Don't hold a valid license at this time;

Q3: How many years of driving experience do you have? (including period with learner's permit)
● 0 - 2 years; ● 2 – 5 years; ● 5 – 10 years; ● 10 + years;

Q4: How often have you typically driven during the last 6 months?
● Daily, or almost (4+ hours most days); ● Daily, or almost (2 - 4 hours most days); ● Daily, or almost (0 - 2 hours most days);
● Weekly (3 - 4 times most weeks); ● Weekly (1 - 2 times most weeks); ● Less than once per week;

[Participants could only continue if they did not answer "Learner's permit" or "Don't hold a valid license at this time" to Q2, "0 - 2 years" to Q3, and "Less than once per week" to Q4.]

Q5: Please indicate your sex:
● Female; ● Male; ● Other: ________; ● Prefer not to answer;

Q6: Please indicate your age:
● 18 - 24; ● 25 - 34; ● 35 - 44; ● 45 - 54; ● 55 - 64; ● 65 or older; ● Prefer not to answer;

Q7: Indicate how well each of the following statements describe your typical driving style:
● Not at all; ● Slightly well; ● Somewhat well; ● Moderately well; ● Very well; ● Extremely well;
[Question order was randomized.]

Q7.1: I accelerate out of intersections faster than other vehicles
Q7.2: I approach red lights and other stops faster than other vehicles
Q7.3: I drive as fast as safely possible
Q7.4: I often push the accelerator or brake all the way down
Q7.5: Loose items in my car often shift backward and forward as I drive
Q7.6: I often feel the force of the vehicle pushing me forward or holding me back
Q7.7: I take every safe opportunity to get ahead in traffic and adjust my speed as needed
Q7.8: I would change my driving style if I was low on fuel and unsure about making it to the station
Q7.9: My driving style would be more accurately called "dynamic" than "smooth"
Q7.10: My driving style would be more accurately called "sporty" than "relaxed"

Q8: Is your driving style more like car X or car Y?

[Figure 2 shows a single frame from the 20 second animation that was auto-played and looped. Car X accelerates and brakes harshly, and car Y moves with more gentle movements. Participants responded with a 6-point slider from Car X to Car Y]
Car X ● 1; ● 2; ● 3; ● 4; ● 5; ● 6; Car Y

Q9: Why do you typically drive with the style that you do? (select all that apply)
● It feels safer; ● It's more enjoyable; ● I arrive faster; ● It's more fuel efficient; ● Traffic conditions require it;
● Road conditions require it; ● It's better for my car; ● It's what I learned/what I'm used to; ● I don't know; ● Other: ________;

Q10: We will refer to car X's style as "Dynamic" and car Y's style as "Smooth"
[The same animation as Q8 was played again. Participants could not proceed until they made the correct matching of car and style to confirm understanding.]
Car X: ● Dynamic; ● Smooth; Car Y: ● Dynamic; ● Smooth;

Q11: Below are four sample frames of some animated interfaces. Imagine each were displayed on your vehicle dash, animated to respond to the forward-backward motion of the vehicle. How effective would each of these displays be in influencing you to drive more smoothly or dynamically than you typically do?
[Participants were presented the displays as shown in Figure 1 in randomized order, with a response prompted for each display.]
● Very effective for driving more smoothly; ● Moderately effective for driving more smoothly;
● Slightly effective for driving more smoothly; ● No effect; ● Slightly effective for driving more dynamically;
● Moderately effective for driving more dynamically; ● Very effective for driving more dynamically;

Q12: What do you like or not like about these displays? [Text entry]

Q13: Does the vehicle you typically drive have a driving efficiency display?
● Yes (instantaneous MPG, gal/100mi, L/100km); ● Yes (other type of display); ● No; ● I don't know;

[Q14-16 were only presented to participants who answered "Yes" to Q13]

Q14: How effective do you think your current vehicle's display is at influencing you to drive more efficiently than you would otherwise?
● Not effective at all; ● Slightly effective; ● Somewhat effective; ● Moderately effective; ● Very effective;
● Extremely effective;

Q15: Relative to your existing display, how effective do you think these new displays would be at influencing you to drive more efficiently?
[Participants were presented the displays as shown in Figure 1 again in randomized order, with a response prompted for each display.]
● Much more effective; ● Moderately more effective; ● Slightly more effective; ● Slightly less effective;
● Moderately less effective; ● Much less effective;

Q16: Is there a particular type of efficiency display you would like to have? [Text entry]

[Q17 was only presented to participants who answered "Yes (other type of display)" to Q13]

Q17: What vehicle do you drive that has the efficiency display you indicated?
● Make; ● Model; ● Year;

Q18: Indicate how well each of the following statements describe you:
● Not at all; ● Slightly well; ● Somewhat well; ● Moderately well; ● Very well; ● Extremely well;
[Question order was randomized, except for position of the attention check, Q18.5.]

Q18.1: I would be willing to drive more smoothly than I do now
Q18.2: I make a conscious effort to drive energy efficiently
Q18.3: I believe a smooth driving style is significantly more energy efficient than a dynamic one
Q18.4: Environmental sustainability and preventing climate change are important to me
Q18.5: Please select "Slightly well"
Q18.6: I make an effort to reduce my personal environmental impacts
Q18.7: I believe efficient driving is a worthwhile way to reduce environmental impacts

Q19: Do you have any comments or ideas regarding this survey? Your feedback is appreciated! [Text entry]

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