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Review article

Information, timing, and display: A design-behavior framework for improving the effectiveness of eco-feedback

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A R T I C L E   I N F O

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A B S T R A C T

Eco-feedback is information about resource (energy, water, food) consumption provided back to consumer(s) with the goal of promoting more sustainable behavior. Effective eco-feedback relies upon an understanding of key eco-feedback design dimensions and how they relate to behavior change. This paper develops a conceptual framework that includes a typology of eco-feedback design dimensions and maps those dimensions on to the behavioral mechanisms of attention, learning, and motivation. To develop this framework, we synthesized, clarified, and expanded on previous discussions of eco-feedback design dimensions across multiple academic disciplines. Our analysis yielded three types of behaviorally-relevant eco-feedback design dimensions: information, timing, and display. Information dimensions include granularity, metrics, valence, and contextual information. Timing dimensions include latency, strategic timing, and frequency and duration. Display dimensions include medium, modality, style, location, audience, and response requirement. Each of these dimensions has implications for eco-feedback salience, precision, or meaning, qualities that correspond to the behavioral mechanisms of attention, motivation, and learning, respectively.

1. Introduction

Eco-feedback was first defined by McCalley and Midden [1] as "information presented during the product-user interaction which prompts the user to adopt energy saving strategies" (p. 2). Early applications of eco-feedback were developed by behavioral and environmental psychologists and focused on providing households with information about their electricity consumption via private digital or paper-based interfaces (see reviews in [2–6]). Applications of eco-feedback have since expanded to address other types of resources (e.g., water), to target other sectors of consumption (e.g., business), and to convey information via public, ambient, and tangible interfaces. Froehlich et al. [7] expanded the concept accordingly when they defined eco-feedback technology as that which provides "feedback on individual or group behaviors with a goal of reducing environmental impact" (p. 1).

Despite the growing diversity of eco-feedback technologies, behavioral theory of eco-feedback has largely been focused on the context of household electricity consumption. The majority of recent eco-feedback innovations have been investigated in the field of human-computer interaction (HCI) and have focused more on design and less on behavioral theory [7]. Environmental and behavioral psychologists have demonstrated the reverse bias in their research on household electricity consumption feedback, by largely neglecting the designed artifact and focusing on empirical evaluation of behavior change. Froehlich et al. [7] noted there is also a lack of communication and integration across these two perspectives. As a result, most of what we know about how eco-feedback can change behavior is based on a relatively narrow range of eco-feedback applications, and thus an insufficient understanding of the range of design dimensions that have an impact on eco-feedback effectiveness.

There is great need for a framework that integrates the knowledge and approaches of HCI and behavioral science to inform the design of more effective and diverse eco-feedback technologies. This paper begins to address this need by inventorying and classifying eco-feedback design dimensions and their implications for behavior change that have been discussed and/or empirically validated in HCI or behavioral science research. First, we review prior related work.

1.1. Related work

A number of researchers have articulated important design dimensions for effective eco-feedback, though most focused particularly on residential electricity feedback. Table 1 summarizes studies that aimed to lay out relatively comprehensive accounts of objective design dimensions with behavioral relevance. For example, in a conceptual

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Table 1
Prior research articulating important eco-feedback design dimensions in various contexts.

Froehlich [8] Residential eco-feedback technology	Karlin et al. [5,6] Residential energy feedback	Wood & Newborough [9] Residential energy in-home display	Fitzpatrick & Smith [10] Residential energy in-home display	Sundramoorthy et al. [11] Residential energy in-home display	Fischer [3] Residential electricity feedback	Hermsen et al. [12] Feedback technologies to disrupt or change habitual behavior
Frequency	Frequency	Place of display	**Behavior and context**	**Design concerns for persuasive feedback**	Frequency	Sign
Presentation medium	Medium	Motivational factor	**Data feedback**	Energy by type	Content	Comparison
Measurement unit	Measurement	Display units	Metrics	Measurement unit	Breakdown	Technology
Recommending action	Combination with other interventions	Display methods	Frequency	Measurement frequency	Presentation	Timing
Comparisons	Comparison	Timescale	Granularity by utility	Appliance monitoring	Inclusion of comparisons	Modality
Data granularity	Granularity	Category	Granularity by appliance	Comparison	Combination with additional information and other instruments	Frequency and duration
Push/Pull	Duration		Usage comparison	Information sharing		Presentation
Location			Representations	Energy saving tips		
Visual design			**Device issues**	Targets and alerts		
Social sharing			Form	Display mechanism and visualization		
			Location	**Design concerns for the home**		
			Engagement issues	Home network		
			Baseline exploration	Privacy		
			Awareness	Aesthetics, fitting and positioning,		
			Querying and diagnosing	Holistic applications		

paper, Wood and Newborough [9] articulated a typology of residential energy feedback display design factors. Fitzpatrick and Smith [10] articulated "a set of design-relevant issues and questions that can form the basis for what makes effective energy use displays" (p. 38) based on several studies and personal accounts of home energy feedback displays. Sundramoorthy et al. [11] articulated important features for persuasive feedback based on results from a focus group of home energy feedback users. In a rigorous meta-analysis of residential energy feedback studies, Karlin et al. [5] tested a variety of feedback dimensions, identified from an extensive literature review, as moderators of effectiveness.

There are limited examples of such work with a broader scope, i.e., beyond the context of residential electricity feedback. For example, Froehlich [8], though his paper was framed to focus on residential energy feedback, drew from literature spanning a greater variety of eco-feedback applications (e.g., commercial building energy displays, sustainable mobility apps, household water consumption feedback) to articulate ten important design dimensions (Table 1). In a subsequent paper, Froehlich et al. [7] reviewed eco-feedback technology research, including 89 papers in the environmental psychology literature and 44 papers in the HCI and UbiComp literature, spanning the most diverse sample of eco-feedback applications of any single paper. Though not a major focus of the paper, their analysis highlighted important design factors similar to those listed in Froehlich [8]. Finally, Hermsen et al. [12] reviewed literature on digital feedback technologies for changing habitual behavior, including at least 28 eco-feedback studies (targeting electricity or water consumption, waste reduction, or eco-driving), and identified design dimensions that impact feedback efficacy in that broader context.

While these were all useful accounts of important eco-feedback design dimensions, none were comprehensive with respect to the broad range of eco-feedback applications. Most were focused on certain types of eco-feedback, particularly residential electricity feedback; none focused broadly, but exclusively, on eco-feedback. Some included considerations beyond objective dimensions of eco-feedback design (e.g., engagement issues), and interactions with other intervention strategies (e.g., prompts and goal-setting). Furthermore, there has not been a coherent conceptual framework that systematically maps objective eco-feedback design dimensions on to their behavioral implications. Building on this literature, the purpose of this paper is to move toward a comprehensive and coherent design-behavior framework that will contribute to more successful eco-feedback designs and more systematic user research and evaluation.

2. Methodology

We conducted a literature review on a wide range of eco-feedback applications across the fields of human-computer interaction and environmental and behavioral psychology. Our process began by identifying a strategic sample of review papers. These included the Froehlich et al. [7] review of HCI and environmental psychology eco-feedback literature, the Karlin et al. [5] meta-analysis of residential energy feedback studies, the Hermsen et al. [12] review of technological feedback for habitual behavior change, and a review of eco-driving feedback studies by Kurani et al. [13]. These reviews were selected to represent the different disciplines engaged in eco-feedback research, most notably psychology and HCI, and to represent the range of eco-feedback applications. Each included a large number of studies (Froehlich [7]: 133; Karlin [5]: 42; Hermsen [12]: 28; Kurani [13]: 27).

We conducted backward searches from these review papers, pulling in papers based on information provided in the reviews. In some cases, we performed additional backward searches from papers identified in the reviews. We also conducted forward searches from Froehlich et al. [7]. We supplemented this method by drawing on literature reviews conducted as part of previous studies within our research lab; these reviews covered diverse eco-feedback applications on the following topics: workplace energy feedback, sustainable mobility/transportation eco-feedback, community-level eco-feedback, and ambient and tangible/physical eco-feedback.

Criteria for inclusion at each of these steps was that the work defined some objective feedback design dimension(s) and either empirically or theoretically related the dimension to behavior change outcomes; studies that measured preference or usability only were not excluded but we did not consider them when determining relationships between design and behavior. We culled direct quotations from studies wherever we found definitions and discussions of eco-feedback design dimensions and their behavioral implications (theoretical or empirically-demonstrated). We compiled all quotations in a document and iteratively sorted them according to similar design dimensions. Finally, definitive names were given to the resulting dimensions and categories of dimensions.

After identifying and naming the design dimensions, we coded them according to their behavioral implications. Our framework for organizing behavioral implications was constructed both inductively and deductively. We considered theoretical assertions and empirical findings in the reviewed studies, but also relied heavily on Feedback Intervention Theory (FIT; [14]), and behavior analytic principles (e.g., reinforcement and punishment, schedule effects, stimulus control, and motivating operations; [15–18]), particularly as applied to the topic of performance feedback by Mangiapanello and Hemmes [19]. These theories were selected due to their applicability to the topic of eco-feedback and focus on observable behavior change as opposed to knowledge, attitudes, intentions, preferences, or usability.

3. Results and discussion

Our analysis yielded three general ***behavioral mechanisms*** by which eco-feedback can be effective: attention, learning, and motivation (Fig. 1). *Attention* refers to the response of attending to or perceiving some stimulus, including types of voluntary and involuntary attention [20]; attention is related to awareness of eco-feedback, and not to be equated with understanding or interest. By *learning*, we refer to associative learning processes, which involves stimulus control and reinforcement of behavior via consequences [17,18]. *Motivation* is defined in behavior analytic terms, referring to any event that makes a behavioral consequence more or less reinforcing [21]. This framework aligns well with Fischer's [3] model, based on a review of relevant psychological theories: "On the basis of our model, we theorized that successful feedback has to capture the consumer's attention, to link specific actions to their effects and to activate various motives (p. 85)."

We also articulated three general ***eco-feedback qualities*** that correspond directly to these behavioral mechanisms: salience, precision, and meaning (Fig. 1). *Salience* refers to how well eco-feedback captures attention, i.e., enters the user's awareness. *Precision* is a concept we adapted[1] from Mangiapanello and Hemmes [19]; it refers to the "precision of the programmed relation between parameters of responding and parameters of the resulting consequences" (p. 61). This concept is applicable to both feedback and operant conditioning. Greater precision between target behavior and feedback (as a behavioral consequence) supports operant learning. *Meaning* refers to how comprehensible and worthwhile eco-feedback is to the user; aspects of eco-feedback design that provide or enhance meaning impact motivation, i.e., the degree to which feedback functions as a reinforcer for target behavior.

Our analysis yielded three types of ***eco-feedback design dimensions*** that have implications for user behavior; they are: information, timing, and display (Fig. 1). Eco-feedback *information* dimensions answer the question, *What information is presented?* Eco-feedback *timing* dimensions answer the question, *When is the information presented?* Finally, eco-feedback *display* dimensions answer the question, *How is the information presented?* The following sections define dimensions within each of these three categories and discuss their implications for the behavioral mechanisms and eco-feedback qualities mentioned above: salience/attention, precision/learning, and meaning/motivation. These relationships are summarized in Fig. 2.

3.1. Information

Eco-feedback information dimensions concern the information presented to the user(s). Two sub-categories of eco-feedback information are granularity and message (Fig. 3). *Granularity* refers to the degree of fine to coarse information provided. *Message* describes the particular content of eco-feedback.

3.1.1. Granularity

There are three types of granularity: *behavioral*, *data*, and *temporal*. Each has implications for the precision of eco-feedback with respect to the behaviors it reflects, i.e., the degree of correspondence between dimensions of the target behavior and dimensions of the feedback (Fig. 4). Greater precision supports learning, as will be discussed in the following sections.

3.1.1.1. Behavioral granularity. Behavioral granularity describes whose behavior and which particular behavior(s) are reflected in the data, i.e., the target consumer(s) and target behavior(s). For example, some eco-feedback reflects the behavior of an individual (e.g., eco-driving feedback that reflects the driver's operation of the vehicle), whereas other eco-feedback reflects the behavior of entire communities, e.g., Oberlin City-wide Dashboard reflects the resource consumption of an entire city [22]. Furthermore, eco-feedback may reflect a specific response (e.g., a shower meter that reflects use of hot water in the shower), whereas other feedback reflects an aggregate of behavior (e.g., a home energy monitor that reflects all electricity-consuming behaviors in the home).

Similar concepts in past energy feedback research are utility, end-use, and appliance granularity, referring to the disaggregation of consumption information by energy source (e.g., gas, electricity), by end-use category (e.g., lighting, plug loads), or by specific appliance (e.g., refrigerator, washer, dryer), respectively (e.g. [2,10,11]). All these only have implications for behavior insofar as they represent the behaviors reflected (i.e., targeted) by the feedback. Framing the idea as behavioral granularity draws attention to the target consumer and behavior rather than the appliance. This idea is consistent with Strenger's [23] assertion that household eco-feedback should be designed by first studying everyday interactions, then designing devices to support those behavioral patterns. Similarly, eco-feedback research confirms the importance of helping the user connect consumption to activities rather than appliances [24,25].

Behavioral granularity is a critical dimension of eco-feedback. Though a general goal, such as reduce consumption, may guide the development of an eco-feedback intervention, the main objectives should include targeting specific behaviors for change. Eco-feedback designers should choose target behaviors deliberately, based on existing knowledge and theory regarding both the technical potential of the behavior for mitigating environmental impact and behavioral plasticity, which is the degree to which consumers may be willing to change that behavior [26]. For example, heating, ventilation, and air conditioning (HVAC) may account for the most energy consumption in a given building (technical potential), but if occupants do not have control over the HVAC system (behavioral plasticity), providing them with feedback on its use would have little impact on energy consumption outcomes.

It is also important to take an ecological view when selecting target behaviors, anticipating and avoiding unintended consequences [11]. For example, Fitzpatrick and Smith [10] discussed how study participants provided with home electricity feedback reduced their use of

[1] Mangiapanello and Hemmes [19] considered feedback latency separate from precision, but we consider latency related to precision.

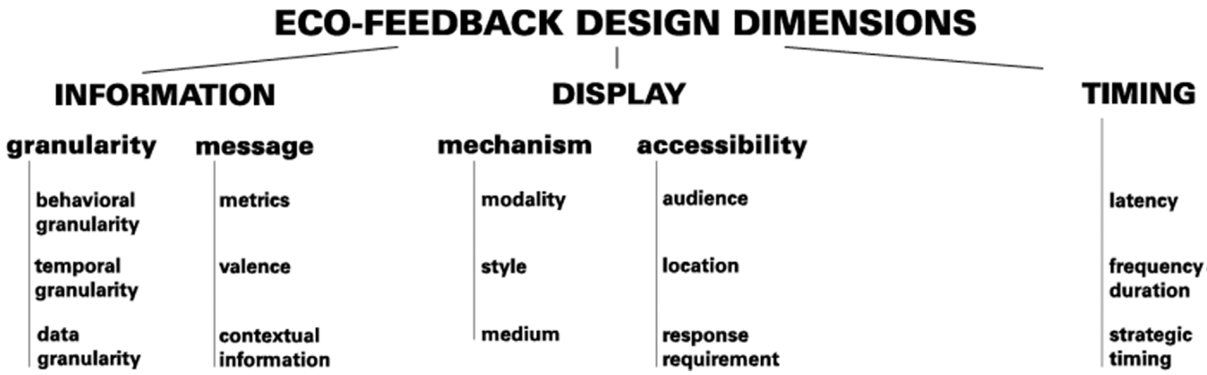

Fig. 1. Typology of eco-feedback design dimensions, with three main categories: information, timing, and display.

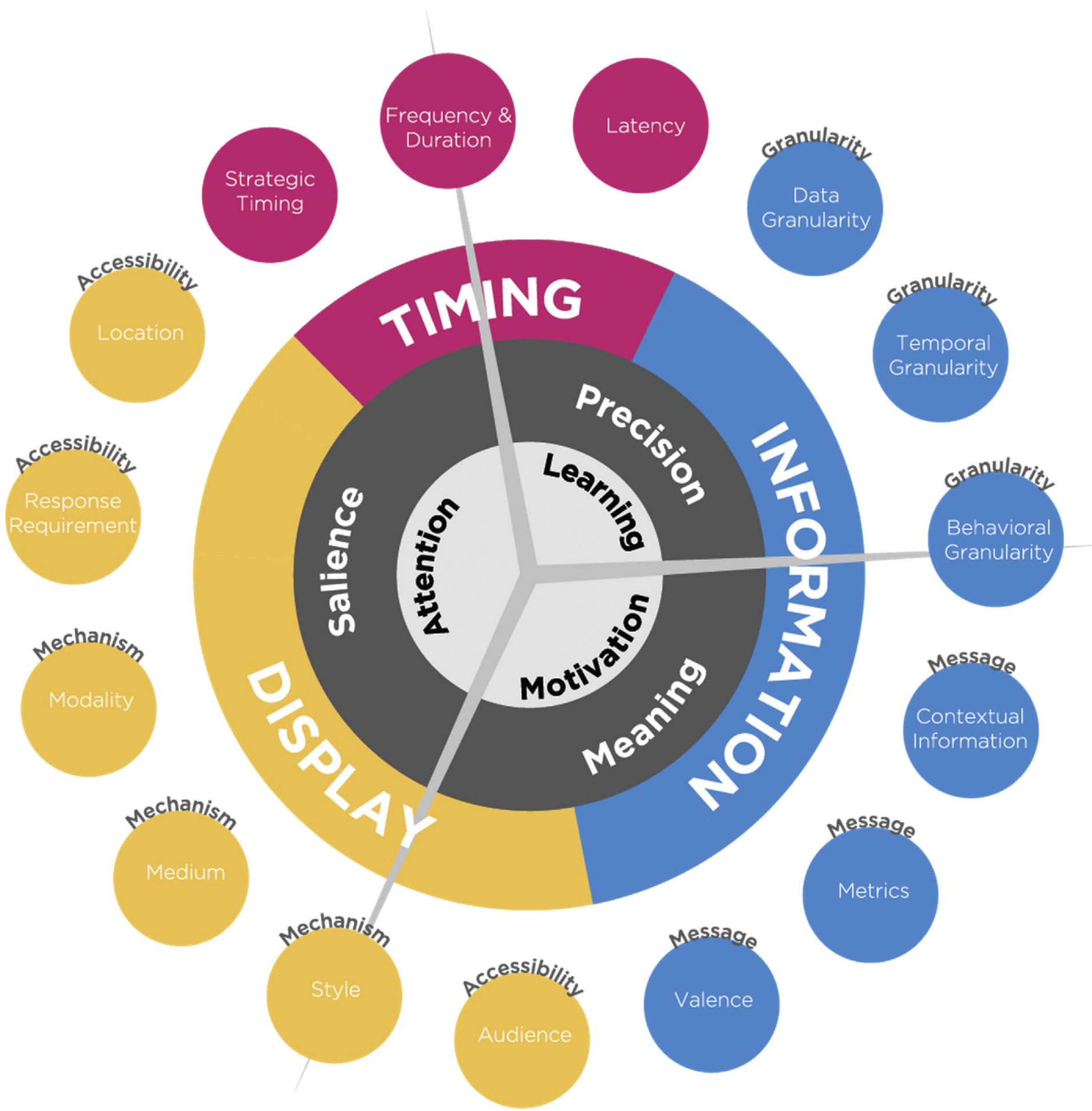

Fig. 2. This diagram represents the design-behavior framework presented in this paper. In the center are three behavioral mechanisms by which eco-feedback can impact consumer behavior. At the next level, three high-level eco-feedback qualities correspond to each behavioral mechanism (e.g., precise feedback promotes learning). The third and fourth levels map eco-feedback design dimensions on to the qualities of salience, precision, and meaning and corresponding behavioral mechanisms for which they have the greatest implications (e.g., style, a dimension of eco-feedback display, has implications for eco-feedback salience *and* meaning, and thus for attention and motivation).

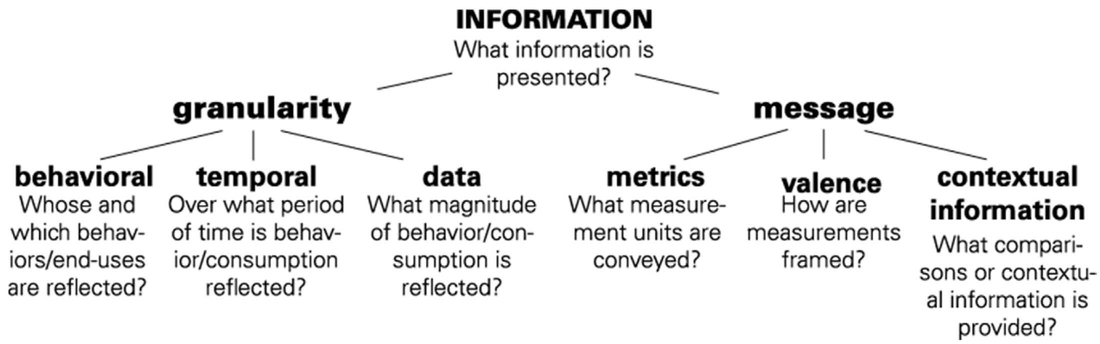

Fig. 3. Sub-categories and dimensions of eco-feedback information.

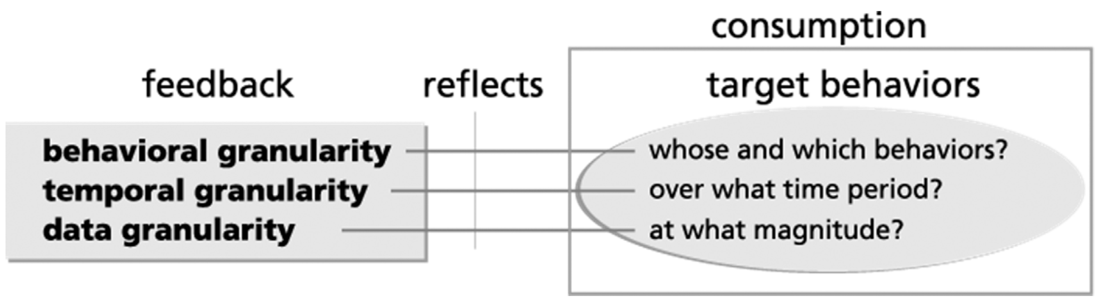

Fig. 4. Dimensions of eco-feedback granularity. This figure illustrates how dimensions of eco-feedback granularity correspond to dimensions of the target behavior. Behavioral granularity defines whose behavior and which behaviors are reflected in the feedback, temporal granularity determines the time period over which target behavior is conveyed, and data granularity defines the magnitude of the target behavior that is reflected in the feedback.

electric kettles, but increased their use of gas stoves for heating water. Gas consumption was not included in the feedback, therefore they were not penalized for transferring consumption to another energy source.

In general, research has suggested that high behavioral granularity, i.e., eco-feedback more specific to the individual consumer and specific behaviors, is both preferred and more effective in reducing consumption [3,10,8,27,28]. Specific eco-feedback provides a precise connection between behavior and consequence, and is thus useful for learning new and complex behaviors [19]. For example, consumption disaggregated by specific appliance reflects more specific behaviors than consumption aggregated at the building level; aggregate feedback may lead the user to believe that their actions have little impact [29]. Furthermore, high behavioral granularity can mean more personalized information, which is engaging to users and affords them with a greater sense of control.

However, there are contexts where high behavioral granularity is not preferred. For example, studies of electricity feedback in office buildings caution against highly disaggregated data as it may enable the tracking of private information about employee activities or adversely affect employees' perceptions of privacy [30,31].

There are also highly successful examples of eco-feedback with very low behavioral granularity, such as the Nuage Vert (meaning "green cloud") temporary art installation by artists HeHe. The installation reflected the behavior of the entire city of Helsinki, Finland, via a green laser outline around a coal plant smokestack's exhaust corresponding in size to the city's energy savings. This effort resulted in approximately 800 kVA (480 kW) decreased energy demand during an hour-long period of organized effort at the end of the installation [32]. Other research in the context of eco-feedback for sustainable mobility also suggests the effectiveness of collective feedback for leveraging social influence and sense of community [33]. Thus, there is sometimes a trade-off whereby eco-feedback may focus on motivating a large community by reflecting collective behavior and goals, but lack precision to support learning; conversely, very personalized and granular eco-feedback may support individual learning, but reach fewer consumers and be unable to take full advantage of social influence strategies to motivate users.

3.1.1.2. Data granularity. We define data granularity as the resolution of information conveyed, which corresponds to the amount of levels, or differentiation provided, in the data. Data granularity is often related to feedback modality (described below with *display* dimensions). For example, numeric data typically have high data granularity, whereas a light that changes colors between green, yellow, and red has low data granularity.

Data granularity helps define the target behavior; in particular, it relates to the magnitude of behavior required to effect changes in feedback. Similar to behavioral granularity, data granularity has implications for the precision with which eco-feedback reflects target behaviors. When feedback reflects very small increases and decreases in the magnitude of target behavior it is more precise and thus more supportive for learning new or complex behaviors.

However, ambient displays often call for reduced data granularity so that information can be absorbed while the user is attending to some other task [34]. There is some support for the effectiveness of ambient eco-feedback (e.g. [35–37]), which will be discussed further in the section on eco-feedback *modality*. Thus, when combined with high salience, low granularity feedback can call attention to a few important levels of information, which might trigger further investigation, at which point higher granularity feedback could be provided to support learning.

3.1.1.3. Temporal granularity. Temporal granularity refers to the time period reflected in eco-feedback data. Temporal granularity has two main levels: instantaneous or accumulated over some duration (e.g., interval-by-interval performance data, average levels, or accumulating totals).

Temporal granularity does not necessarily directly reflect the duration of the target behavior. For example, what is often referred to as real-time feedback (what we would call in this paper instantaneous, immediate, and continuous feedback) may reflect momentary consumption, but not momentary behavior. For example, a home energy monitor might display real-time power demand in the home, e.g., in watts or cost per hour. The user may glance at the feedback while sitting in the living room watching television, after having started the dishwasher and electric dryer several minutes earlier. The feedback will be reflecting instantaneous consumption but the relevant behaviors include momentary behaviors that occurred in the recent past (the discrete acts of starting the dishwasher and dryer) and the ongoing, prolonged behavior of watching television.

Eco-feedback designers should consider the natural duration of the target behavior(s) and resultant consumption patterns when determining the temporal granularity of the feedback. In some cases it will make sense to match them. For example, eco-driving feedback specific to acceleration efficiency is sometimes provided in terms performance during a given acceleration event, which is typically how the behavior naturally occurs, rather than continuously or over the course of an entire trip.

van der Voort et al. [38] eloquently described the importance of striking a balance with temporal granularity: "Achieving the right level of temporal granularity for optimization is important; too coarse and many opportunities to improve performance will be missed. Conversely, a fine-grained approach will operate in local optima which may or may not represent the global optimum over a longer period of time" (p. 281).

Rather than striking a balance, other research suggests distinct roles for each low and high temporal granularity. Specifically, high temporal granularity generally enables a more precise correspondence between feedback and behavior, which supports learning, whereas low temporal granularity enables goal-setting and retrospection. For example, Darby [2] described the utility of accumulated household energy consumption feedback for assessing long-term patterns and trends for large energy loads and the impact over time of equipment investments or other changes; whereas instantaneous data can reveal impacts of behavior with respect to smaller end-uses. In the context of eco-driving feedback, studies have shown instantaneous feedback (e.g., momentary fuel efficiency) is used primarily for experimentation and learning new behaviors, whereas accumulated feedback (e.g., average fuel-efficiency) is used primarily for goal-setting and assessing overall performance [39,40]. As mentioned later with regard to feedback standards, it is also useful to provide information at multiple time scales for comparison [25].

Temporal granularity is often conflated with latency and frequency (discussed in section on *timing*), which characterize the timing of the information displayed, not the information itself. Instantaneous data are often presented continuously during the relevant behavior, thus immediately reflecting changes (often called real-time feedback), but this is not necessarily the case. Accumulated data can also be presented continuously, e.g., running average fuel economy gauges, and immediately after prolonged behavioral events, e.g., an efficiency score at the end of a driving trip. On the other hand, the presentation of instantaneous data can, theoretically, be delayed and/or presented infrequently. An example of the latter would be a simple audio or visual notification when consumption levels exceed some threshold. These issues are discussed further in the section on eco-feedback timing.

3.1.2. Message

Dimensions of the eco-feedback message include *metrics*, *valence*, and *contextual* information. These dimensions pertain to how data is framed for the user, and they have implications for how meaningful the user perceives the feedback to be, and thus their motivation for responding to it (Fig. 1). Fig. 5 depicts message dimensions, which are described below.

3.1.2.1. Metrics. Quantitative information in eco-feedback is associated with a metric. Metrics can include direct measures of resource consumption, such as power demand (e.g., watts, kilovolt-amps, miles per gallon) or resource usage (e.g., kilowatt-hours, gallons per day, hours of use). Alternatively, or in addition, direct measures may be translated to other metrics for the user, such as resource cost or environmental impacts of consumption (e.g., kilograms of carbon dioxide emissions).

Direct and accurate measurements enable objective analysis of the facts. When educating consumers about the actual mechanics of resource consumption is a goal of eco-feedback the designer would want to include direct measures of resource consumption in scientific units. However, there are two main reasons to consider other types of metrics: (1) Consumers may not understand scientific metrics; (2) Direct and scientific metrics may not motivate consumers to engage with eco-feedback.

Energy as a utility is an abstract concept; it is invisible, intangible, and complex. As a result, standard energy metrics are not well understood by consumers [3]. This is likely not the case for some other resources that might be the target of eco-feedback, such as water. Research suggests that energy cost is often how consumers perceive energy use [41] and thus is a useful metric for making energy more tangible [42,28]. Scores (e.g., percentage points) are sometimes used in eco-feedback; they are generally more familiar and easy to understand. However, indirect metrics like cost and score may sacrifice accuracy, and thus can be misleading [8]. Hours of use of resource-consuming appliance is an underexplored direct metric that avoids the technical complexity of standard energy metrics without sacrificing accuracy [30].

Direct metrics of resource consumption also may not motivate behavior change if they do not convey personal consequences of behavior. Cost is a classic example of translating consumption into a motivating metric; however, if monetary amounts presented in eco-feedback are negligible they may actually be a disincentive to reduce consumption [10,25,95]. Metrics that increase consumers' awareness of the consequences of their behavior for their community (e.g., air pollution) or the environment (e.g., global warming) may motivate behavior change by activating moral norms [43,44]. Examples include scientific metrics of carbon emissions; however, like energy, this concept is invisible, intangible, and unfamiliar to most consumers. Emissions can be further translated into more tangible, visceral, or familiar terms, such as emissions equivalent in trees sequestered or seconds of volcano eruption (Fig. 6).

In sum, there is a distinction between direct, scientific metrics to promote an accurate understanding of resource processes and metaphorical or emotionally evocative metrics to persuade consumers that the information is meaningful and thus motivate behavior change. Since knowledge of resource processes and motivational factors vary widely among consumers, it is important to understand the target consumer or community when determining metrics [10,33]. Providing multiple metrics and/or allowing for customization are promising strategies [3,25,39].

3.1.2.2. Valence. Additionally, information may be framed positively or negatively, e.g., carbon dioxide emitted or offset, resources saved, used, or wasted; the sign of measurement units can also be considered valence [12]. In terms of relevant theory, Schwartz's Norm Activation Model [44] implies that negative valence may be appropriate for eco-feedback to increase awareness of the consequences of consumption (which are negative), thereby increasing motivation via moral/pro-environmental norms. Additionally, the concept of loss aversion in decision theory would suggest that negative valence may be more effective. On the other hand, behavior analytic principles [15] might suggest that positively-framed feedback could more likely function as positive reinforcement, creating a better user experience, whereas negatively framed feedback might be more aversive.

Valence has not often been considered in the eco-feedback literature. We only found one study that investigated valence; Jain et al. [46] found a greater effect for positive points feedback compared to negative points in terms of user engagement. As previously mentioned, a popular type of metaphorical metric in eco-feedback is the translation of CO_2 emissions to trees required to offset the same amount or, a positive

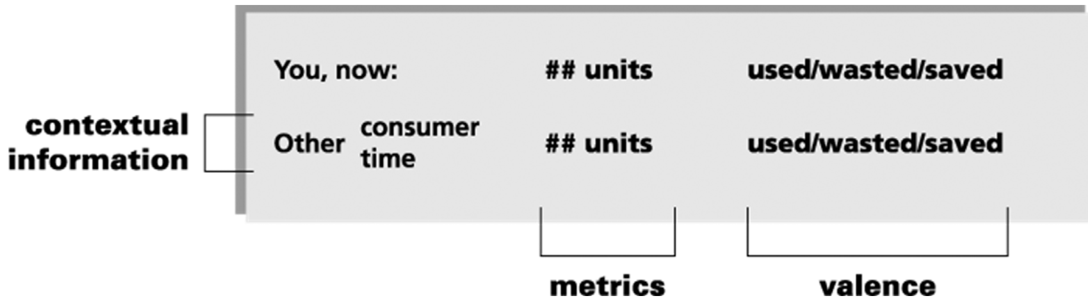

Fig. 5. Dimensions of eco-feedback message. This figure illustrates how eco-feedback frames information for a user. As a targeted user, you may see your own behavior reflected in terms of some metric and valence (e.g., kilowatts used) along with contextual information (e.g., comparisons to others or your own past behavior).

valence, trees spared by CO_2 saved. We have found no research comparing the effectiveness of these alternatives. Valence could be an important area for further research.

3.1.2.3. Contextual information. According to Feedback Intervention Theory (FIT; [14]), feedback can regulate behavior by allowing comparison of performance to a standard. Eco-feedback often includes a feedback standard. In the context of home energy feedback, Fischer [3] noted that "comparisons may stimulate specific motives for energy conservation, for example, a sense of competition and ambition…. They also make transparent whether consumption in a certain period or of a certain household is "out of the norm", thereby capturing the consumer's attention, alerting him to a potential problem and activating the search for reasons and redress" (p. 86).

There are several types of standards that can be provided in eco-feedback, including historical, social, and goal. Historical or self-comparisons enable comparison of an individual's or group's current or recent behavior to their past behavior, e.g., this month's energy consumption compared to last month, an average month, or the same month of the previous year. Social, normative, or peer comparison, sometimes called benchmarking, presents an individual's or group's performance compared to the performance of comparable individuals or groups [47]. Goal comparisons enable consumers to compare their performance to a target or optimal standard (e.g., Fig. 7). Other contextual data can serve as a feedback standard even if it is not explicitly framed as a goal, e.g., estimated fuel economy for a vehicle or expected driving range.

There is empirical evidence for the effectiveness of historical, social, and goal comparisons in eco-feedback [10,42,44,50]. In a rigorous meta-analysis of home energy feedback studies, Karlin et al. [5] found that goal comparisons were most effective, followed by historical comparisons, then social comparisons. In college dorm and workplace consumption reduction campaigns, social comparisons and competitions have been effective [51,97]. Petkov et al. [52] considered a wide variety of motivational factors related to social comparisons in energy feedback.

An important consideration is the size and direction of the feedback-standard gap, i.e., the difference between performance and standard. Research suggests moderately difficult, but achievable goals, e.g., a performance-standard gap of 15% in one study [53], are more effective than goals that are too easy or too difficult [54,55]. In terms of social comparisons, research has shown that, while underperforming compared to peers can motivate improvement, outperforming peers can be a disincentive to improvement [56]. In terms of historical comparisons, Pierce et al. [29] noted that they can create a perception of baseline as goal, so the user does not aspire to consumption reductions, but is pleased just to maintain the status quo. Furthermore, Froehlich [8] noted that historical comparisons as feedback standards can become progressively more difficult to attain if performance improves over time.

Another strategy to consider when designing eco-feedback is to provide multiple standards. For example, social comparisons can be combined with historical comparisons by presenting the current and past performance of both the target consumer and some similar consumer(s) [46]. Multiple of the same type of comparison can also be useful, e.g., efficiency scores for the past day, week, and month. Feedback standards may also be more effective if they are adaptive, changing based on performance to support gradual improvement [57].

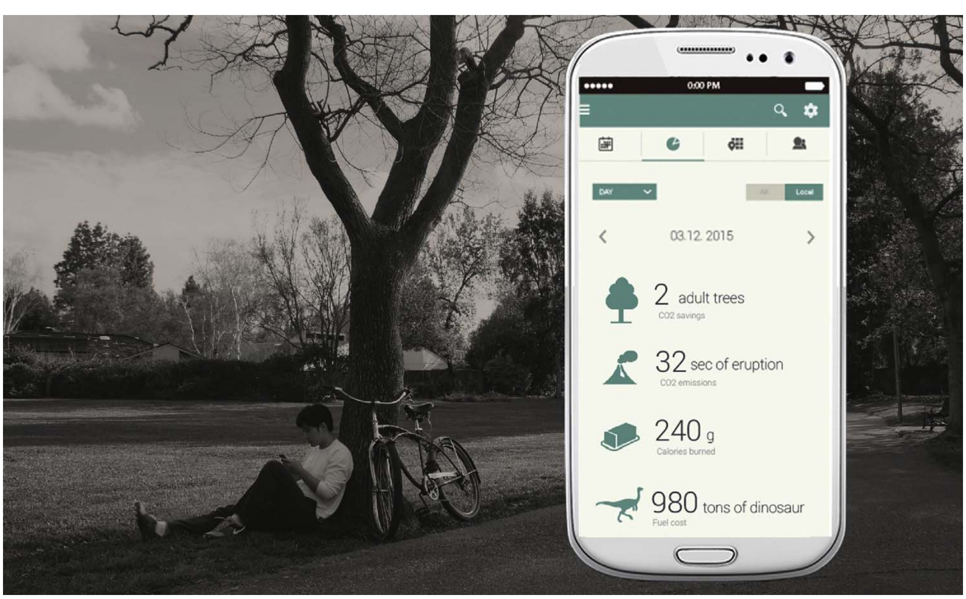

Fig. 6. An Android app called EcoTrips (ecotrips.ucdavis.edu) is designed to promote the target behavior of walking or biking for local trips (less than 3 miles). It allows users to frame the consequences of their travel behavior in terms of different scientific or metaphorical metrics they may find comprehensible and motivating. See Park et al. [45] for further details.

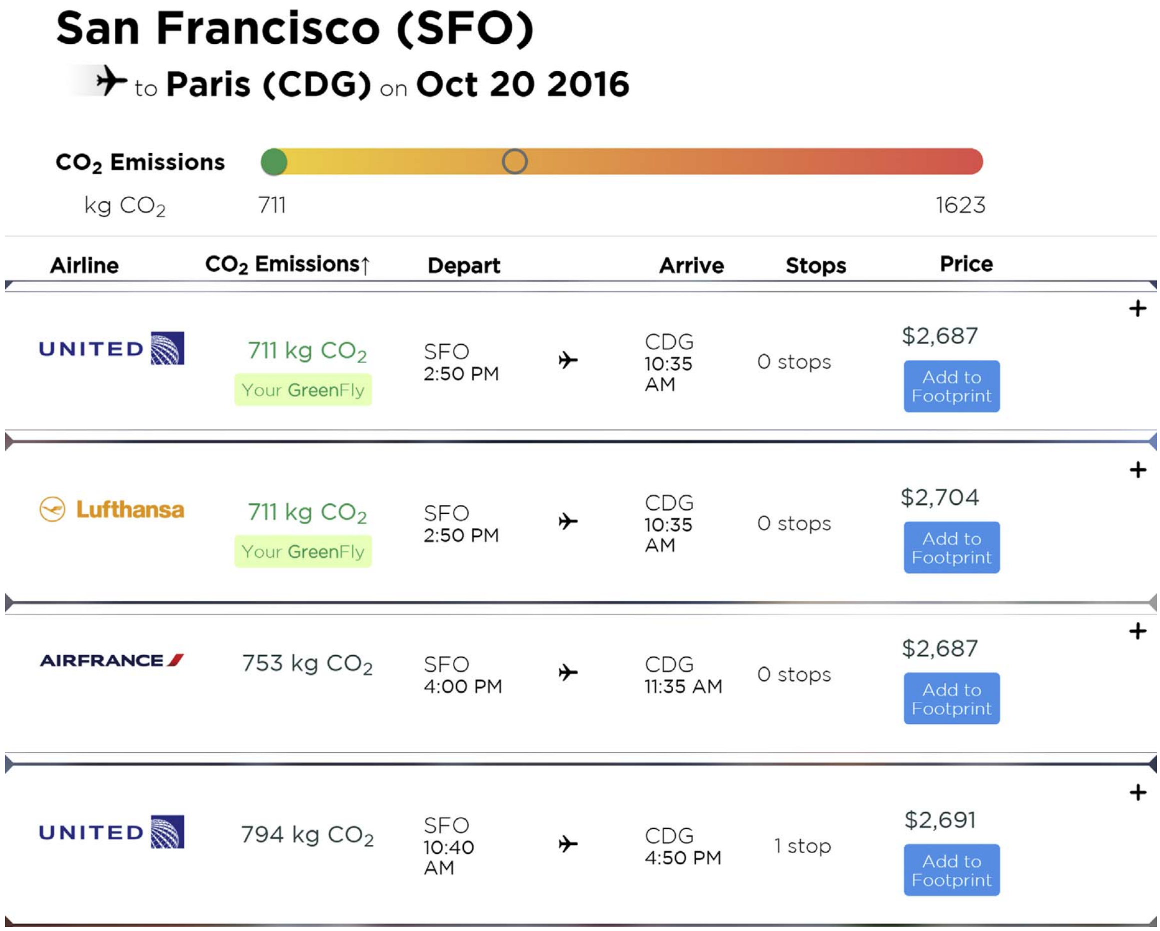

Fig. 7. Flight search results on GreenFLY (greenfly.ucdavis.edu) highlight the lowest-carbon flight(s) as a standard for users to compare among flight alternatives. See Sanguinetti et al. [48,49] for further details.

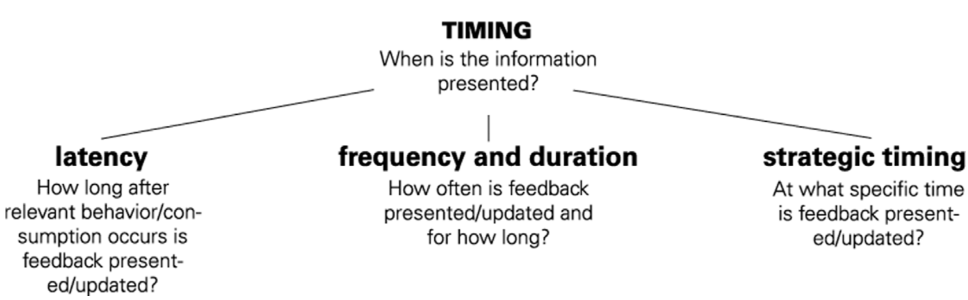

Fig. 8. Eco-feedback timing dimensions.

Feedback standards are a critical aspect of gameful design, the use of game design elements (e.g., points, levels, leaderboards, badges, and challenges) in non-game contexts [98], which is leveraged in many eco-feedback technologies [59–61,22]. Leaderboards involve social comparison and levels involve adaptive feedback standards.

In addition to feedback standards, other contextual information may be provided to help users understand their resource consumption [39]. For example, weather influences energy consumption, so including this information in the interface could help users identify patterns in the data. Energy price is another important factor if it varies, e.g., time-of-use or peak pricing; notifications regarding changes in price could motivate behavior change; "a customer can decide, for example, whether it is worth delaying running a dishwasher or clothes dryer until a lower-price time" (). It could also be useful to incorporate other goals besides mitigating environmental impact based on the target users' priorities, e.g., a navigation system or app that allows a driver to search for an eco-route (i.e., one that will use less fuel) that will not extend the trip by more than five minutes, thus balancing goals to save energy and time [62].

Eco-feedback can also integrate information about the source of energy or water consumption to provide context for the user. For example, Keirstead [63] found that household monitors displaying PV generation information had a notable influence on behavior (e.g., energy consumption reductions). Conveying the complete resource process from source to waste, rather than consumption information alone, can promote systems thinking and a sense of connectedness to ecological systems, which may motivate responsiveness to eco-feedback [64,65].

3.2. *Timing*

Dimensions of eco-feedback timing concern the timing of information presentation, particularly in relation to the target behavior (Figs. 8 and 9). They include *latency*, *frequency and duration*, and *strategic timing*.

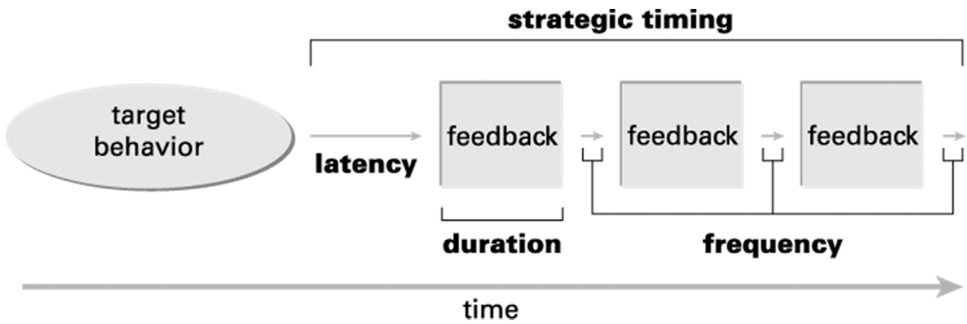

Fig. 9. Dimensions of eco-feedback timing. This figure illustrates how eco-feedback is timed in relation to the target behavior it reflects. Feedback may be presented immediately after the target behavior, it may be presented continuously or at discrete time points for some duration, and presentation may be strategically planned for times the user is most receptive or able to respond.

Each timing dimension has implications for either eco-feedback precision and/or salience, and thus for user learning or attention, respectively (Fig. 1).

3.2.1. Latency

Latency refers to the immediacy of eco-feedback after the target behavior. Basic research on human behavior has demonstrated an inverse relationship between feedback delay and successful performance [19]. Similar to highly granular feedback, immediate (or concurrent) feedback is more precisely related to the target behavior than delayed feedback. Immediate eco-feedback can best support learning, and is especially important when target behaviors are new or complex. Simple behaviors may be easily acquired despite delays in feedback [66].

Delayed feedback may be temporally too far removed to function as reinforcement for the target behavior, i.e., unable to support basic learning processes. However, delayed feedback can support reflection and thus trigger a more complex learning process (i.e., mediated by verbal rules the user learns about relationships between their behavior and its consequences). Immediate feedback can also support these more complex learning processes as links are easily made between behavior and consequences [3,31].

3.2.2. Frequency and duration

We use the term *frequency* to refer to the frequency with which feedback is updated, i.e., not when it is available (e.g., daily feedback could be continuously available). Eco-feedback frequency can be constantly updated or updated at discrete time points–typically at regular intervals, e.g., monthly mailings of household energy or water reports. For computerized eco-feedback, frequency is "influenced by the measurement, data logging, storage, retrieval, processing and presenting requirements." ([9], p. 500).

Energy feedback research suggests that frequent feedback is preferred [42] and more effective [22] compared to less frequent feedback. Similar to immediate and granular feedback, frequent feedback is generally more likely to reveal the impacts of target behavior, as it enables the user to identify changes in feedback that may relate to their behavior. Theoretically, highly data granular feedback that updates frequently, such that the information is changing rapidly, could overwhelm users' cognitive resources [12]. It is also possible that frequent feedback could become tedious or routine such that users stop attending to it [19]. Therefore, feedback displays with lots of information might alternate between different information to avoid information overload and keep users engaged [67].

Frequency is closely related to the *duration* of feedback presentation. For example, the term *continuous* can describe both frequency and duration–feedback updated and presented continuously, i.e., *real-time*. In the literature, duration has been used to refer to the length of a feedback intervention rather than to characterize the feedback itself (e.g. [12,5]). Duration of feedback presentation has received less attention likely because eco-feedback technologies are often available on-demand (e.g., web-based and mobile apps). Also, there has been a major focus on the technical capacity to deliver *real-time* feedback such that the idea of purposely abstaining from presenting information has not often been considered. Further research is needed to understand optimal frequency and duration for various eco-feedback technologies.

3.2.3. Strategic timing

Feedback presentation can occur at strategic times, when consumers are most able or likely to attend to and respond to it, rather than continuously/on-demand or at regular intervals. For example, households might prefer to have eco-feedback accompany their utility bills or to receive it when something has changed [10]. Motion sensors can be used to trigger feedback displays when consumers are nearby. See Fig. 10 for another example of this kind of strategic timing.

Another type of strategic timing is to present feedback only contingent on the target behavior, e.g., a shower meter that is only activated when the shower is running or haptic feedback (i.e., counter-pressure) from an accelerator pedal when it is pressed. This is a very natural arrangement that makes good sense from a behavioral perspective as it makes the connection between behavior and feedback quite clear. However, it has been uncommon in energy feedback which tends to target energy consumption more broadly, encompassing a myriad of behaviors.

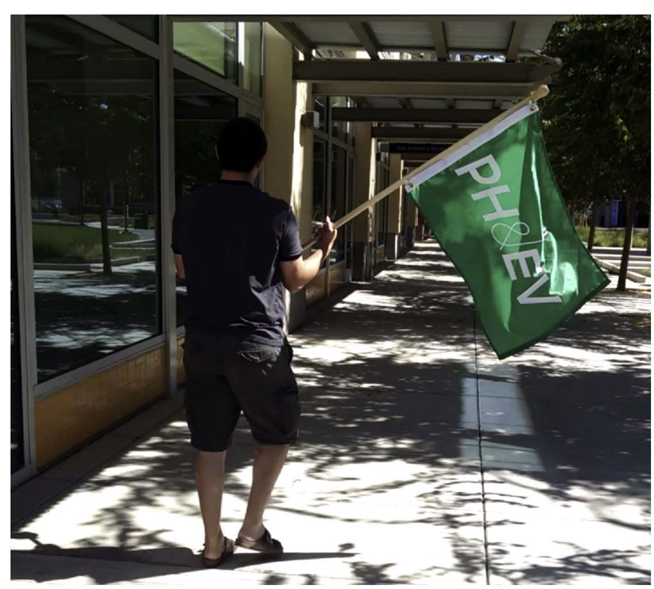

Fig. 10. Energy feedback at a planned zero-net energy (ZNE) office was presented via a flag ceremony performed three strategic times per day (9:00 a.m., 12:00 p.m., and 4:00 p.m.) when occupants were most likely to be present and able to pay attention. A green flag and positive music indicated consumption was at or below a ZNE target for the previous period; a red flag and negative music indicated consumption above that threshold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

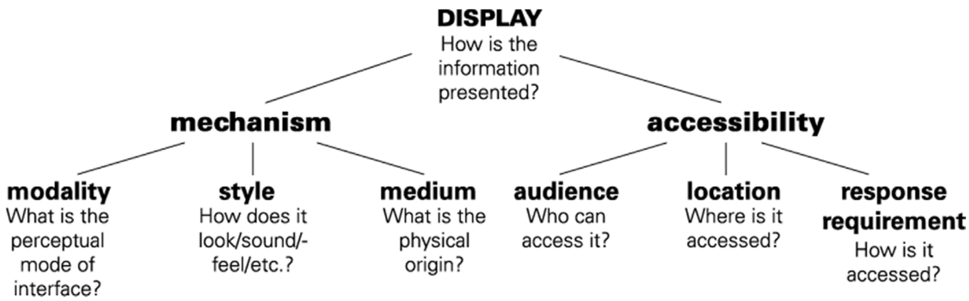

Fig. 11. Sub-categories and dimensions of eco-feedback display.

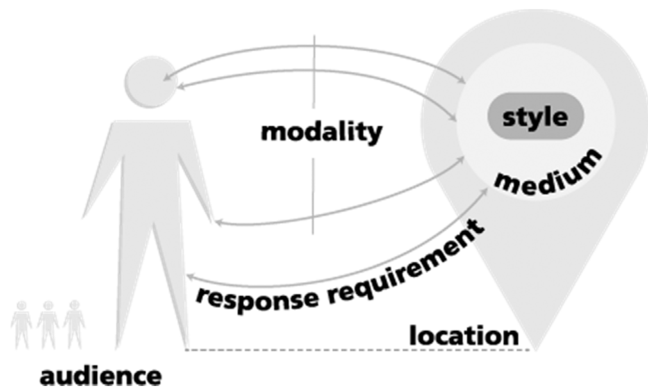

Fig. 12. Dimensions of eco-feedback display. This figure illustrates dimensions that describe who can access eco-feedback and how. Feedback interfaces vary in terms of medium, style, and modality of the designed feedback artifact as well as its location, accessibility to the user and perhaps a broader audience, and the response effort required to gain accesis.

3.3. Display

Dimensions of eco-feedback display characterize the formal characteristics and physical situation of the designed artifact (Fig. 12). We identified two types of display dimensions: the *mechanism* of feedback delivery and *accessibility* (Fig. 11). Each display dimension has implications for eco-feedback salience and/or meaning, and thus for user attention and/or motivation (Fig. 1).

3.3.1. Mechanism

We identified three dimensions related to eco-feedback delivery mechanism: *modality, style,* and *medium.*

3.3.1.1. Modality. Eco-feedback differs in terms of the perceptual mode of interface. The primary perceptual modes are visual, auditory, or tactile. Theoretically, taste and smell could be modes of eco-feedback, but we have not seen examples of these. The predominant mode of eco-feedback is visual, but there are some excellent examples and discussions of auditory and tactile eco-feedback [60,31,68].

Ambient displays are a special class of modality that provide information via subtle, aesthetically pleasing changes that can be absorbed while one is attending to some other task. Critical features include abstracting the data (reducing information granularity) so the user can understand it from the periphery of their perception, varying the salience of the display to correspond to varying importance of different information provided (called notification levels), and the transitions that occur between notification levels to attract attention [34]. There is some support for the effectiveness of ambient eco-feedback in promoting energy savings [37,32], load shifting [36] and increased awareness of energy use ([35]).

Most common examples of ambient eco-feedback involve colored lights, e.g., in on-board vehicle eco-driving feedback displays [69] and in-home energy feedback monitors [60,37,22]. Typical displays use the symbolic red-yellow-green color scheme, though more creative designs can be found [70]. A significantly scaled-up example of ambient eco-feedback is the Nuage Vert installation described earlier [32].

Petersen et al. [22] categorized tactile, auditory, and ambient visual eco-feedback as experiential. Tangible, highly interactive, and virtual reality displays might also be included in this category. Research projects called STATIC! and Switch! at the Interactive Institute in Sweden involved the conceptualization and prototyping of various products that would constitute tangible eco-feedback [59,71]. For example, some of their designs used materials that physically changed in response to energy consumption, such as a lampshade that became crinkled over time in response to use of the light within and patterns on bathroom tile that would disappear over the course of a long, hot shower. The effectiveness of tangible eco-feedback is largely unexplored.

Hermsen et al. [12] provided an excellent summary of choices for feedback modality and the relationship between modality, salience, and information granularity: “An optimal modality choice depends on the possibility of disruption and the need for detail” (p. 64). As previously mentioned, ambient modalities may be highly salient, thus minimizing disruption, but are low granularity, thus lacking capacity for detail. For example, auditory and tactile feedback are relatively more popular in the context of eco-driving feedback since the driver has other visual priorities (e.g., [58]). Computerized visual eco-feedback has the greatest capacity for detail.

Research also suggests the “value of employing multiple modes of information delivery that tap into multiple senses and allow individual users to access information according to their preferences” (). For example, a combination of visual and haptic force feedback from the accelerator pedal has been found to be more effective than either alone to promote eco-driving [72]. In a focus group for the participatory design of workplace energy feedback, visualization style was “the most debated theme” (), implying the subjectivity of style preferences.

3.3.1.2. Style. Styles of visual eco-feedback include numbers, text, graphics (e.g., charts, graphs), movement, animation, pictures, icons, colors, and lights. Hermsen et al. [12] noted that “visual design aspects and aesthetics determine the attitude towards a design as well as the perceived ease of use … Moreover, a clear design might aid in emphasizing important information, personalizing the feedback and improving the fluency of feedback.” Eco-feedback style encompasses these considerations.

Pierce et al. [73] described three types of eco-visualization, defined by Holmes [61] as “methods to inspire environmental stewardship through dynamic data visualization in media art” (p. 2). Pragmatic eco-visualization aims to clearly communicate resource processes via scientific visualization elements (e.g., numbers, charts, and graphs). Artistic visualization leverages persuasive imagery to create meaning for users; note this is similar to the distinction between scientific and metaphorical metrics. The third category, informative art, is in between pragmatic and artistic; it is “decorative … not immediately recognizable as a data-visualization”, can be “integrated more long-term within the building environment”, and “can easily be read to provide clear information, but only after the user has recognized the display as a data-visualization and learned how to read it” ([73], p. 7).

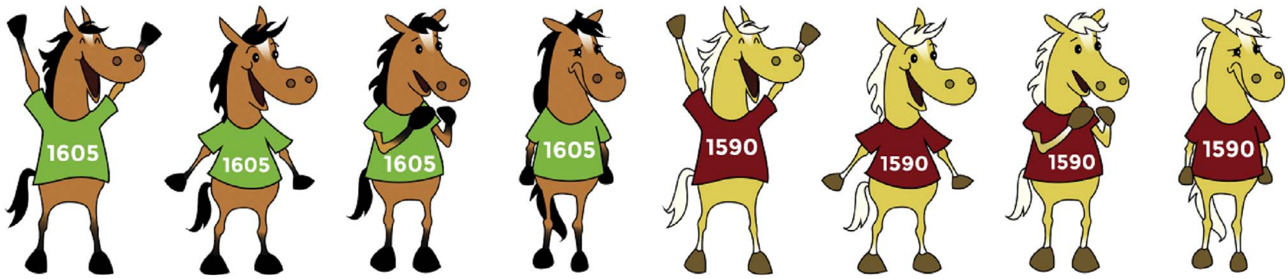

Fig. 13. These horses are empathetic gauges. They are featured on an energy dashboard for four office buildings; each building has its own horse mascot. Each horse's mood changes to reflect its building's energy consumption.

Some research challenges the general appeal of complex pragmatic visualizations, suggesting many users "do not want to spend a lot of time reading text or interpreting graphs" ([74], p. 4). There is not much research on the relative effectiveness of different types of graphs, charts, and numeric eco-feedback, though some insights can be found [75,76,9]. In one study [10], users expressed preference for bar graphs with a hierarchy of temporal granularity, e.g., month, day, half-hour. Other research suggests that map-based scientific data visualizations are more engaging than bar charts [77].

Map-based data visualizations can also be artistic; Oberlin's City-wide Dashboard (http://environmentaldashboard.org/brd/) is an example. It is an engaging pictorial map-based visualization of resource flows, illustrating connections between resource production and source, consumption behavior, and waste. As previously referenced, research indicates this uniquely styled dashboard promotes systems thinking and connectedness to ecological systems, which motivate responsiveness to eco-feedback [64,65].

Artistic visualizations also include empathetic gauges [22,65], such as smiley faces and familiar or relatable animals, plants, or landscapes that exhibit moods or changes in health based on resource consumption (Fig. 13). These styles often leverage biophilic design [78,79], which refers to the use or imitation of elements of nature (plants, animals, and materials) in design, and is based on E. O. Wilson's biophilia hypothesis, which contends that humans have an innate affiliation with other living things. Eco-feedback often incorporates visualizations of plants and animals to raise awareness of environmental impacts and increase user motivation to conserve. Research suggests that biophilic design and empathetic gauges can be effective strategies in eco-feedback [78,80–82,22]. For example, Chiang et al. [80] found that smiley/frowny faces were more effective than numeric feedback or analog gauges, though the difference was not statistically significant.

Other research comparing artistic and pragmatic eco-visualizations suggests they complement each other [83,81]. Kim et al. [81] compared a bar chart visualization to imagery of a coral reef reflecting study participants' computer idle time (the greater proportion of idle time, the less healthy the reef in terms of number of fish, etc.). They concluded that iconic metaphor (the reef) promotes emotional attachment, while indexical representation (the bar chart) supports retrospection. Similarly, Froehlich et al. [83] found that participants desired numeric feedback in addition to iconic (imagery of trees and polar bear ecosystems), in the context of a mobile app tracking transportation behavior and associated environmental impact, in order to gain a more accurate understanding of current and past performance.

Style considerations should be extended to the medium of eco-feedback, described next, not just the information display. This is relevant when the feedback has a dedicated medium, but less so with online feedback that can be accessed via web or mobile app. For example, Riche et al. [84] found that aesthetics of an in-home display (IHD) of electricity feedback influenced preferences, particularly among women, who indicated style would influence where they placed the device (relating to another important dimension, *location*, discussed later).

3.3.1.3. Medium. We refer to the physical origin of an eco-feedback display as the medium; this has also been referred to as feedback source [66]. As previously mentioned, the medium of early eco-feedback displays was typically paper. Digital displays are now the most prevalent, though paper-based energy and water reports are popular utility programs (these are also sometimes provided digitally via email).

Digital eco-feedback mediums include desktop and laptop computers, large computer monitors, standalone displays (devices with the sole purpose of providing feedback), tablets, embedded (in appliances), and smartphones. There are countless and ever-growing possibilities for physical eco-feedback mediums, e.g., Fig. 14. Although the focus of this paper is eco-feedback technology, it is important to remember that humans can also be the medium of eco-feedback or involved in its delivery. Incorporating humans in the delivery of eco-feedback may leverage social influence factors such as accountability and sense of community (e.g., Fig. 10).

Residential energy feedback research suggests that computerized feedback, particularly web-based, is more effective than paper-based [3,5,85]; however, users have different preferences for computerized eco-feedback mediums [86] and appreciate the flexibility of accessing information across a variety of media [74]. Large or novel mediums (e.g., [87]) and those already used frequently by the target consumer(s) may receive more attention. Portability of the display may also be desirable [10]; this idea relates to display location which is discussed in the next section concerning accessibility.

Fig. 14. This large metal statue was built to convey information about environmental impacts of collective behavior via movement, sound, and light. An example of spectacle computing and a new generation of tangible and ambient eco-feedback, the monument is intended to inspire more sustained engagement than conventional data visualizations.

Table 2
Areas for future or further research for each eco-feedback design dimension.

Design Dimension	Areas for Future Research
Behavioral Granularity	Antecedents and behavioral processes related to effective group-level eco-feedback; creative ways of disaggregating data by occupant/activity
Data Granularity	Parametric analyses [15] to define optimal levels of data granularity for different eco-feedback applications
Temporal Granularity	Exploring how low temporal granularity feedback may serve as a feedback standard for related high temporal granularity feedback
Metrics	Further studies of the effectiveness of hours of use as a metric as a direct and relatable metric
Valence	Measuring the relative effectiveness of positive and negative framing of different types of metrics in different contexts with different user groups
Contextual Information	Parametric analyses [15] to define most effective ranges of different types of eco-feedback-standard gaps
Latency	More/new applications of immediate or concurrent eco-feedback that is also in situ and ambient
Frequency & Duration	Parametric analyses [15] of eco-feedback frequency and duration in different applications
Strategic Timing	Comparing the effectiveness of strategically-timed eco-feedback versus interval, continuous, or on-demand presentation
Modality	Comparing the effectiveness of auditory eco-feedback versus visual-ambient, over long interventions or with maintenance (follow-up) checks
Style	Applications and empirical studies that focus on aesthetics of the eco-feedback interface or medium
Medium	Applications and empirical studies of tangible/physical eco-feedback
Audience	Applications and empirical studies of public eco-feedback
Response Requirement	Articulating/inventorying strategies to reduce response requirement for various types of eco-feedback
Location	Developing criteria for appliances to identify when embedded displays might be successful, and testing those applications

3.3.2. Accessibility

Dimensions of accessibility describe who can access eco-feedback and how easily. They include the *audience* to which eco-feedback is made available, which includes targeted consumers (whose behavior the feedback reflects), but may also include others. They also include *response requirement* for targeted consumers to access the eco-feedback and, relatedly, feedback *location*. Response requirement and location have implications for feedback salience and thus for user attention; Froehlich [8] noted, “It’s likely that highly accessible information … would fare best in raising awareness” (p. 6). Audience has implications for user motivation, as detailed below.

3.3.2.1. Audience. The simplest distinction in terms of who can access eco-feedback is whether it is accessible only to the target consumer(s) or to a broader audience, though many variations of publicness are possible. Large physical or ambient displays such as Nuage Vert [32] or that in Fig. 14 are easily recognizable as public, but interfaces that tend to be accessed on personal electronic devices, such as websites and mobile apps, can also supply public eco-feedback, e.g., through social network sharing [8]. Building dashboards or other computerized eco-feedback can be provided on large monitors or kiosks in public spaces to encourage social interactions while engaging with the feedback.

In usability testing of energy feedback displays, Lehrer et al. [28] found that participants appreciated social sharing features, i.e., sharing energy consumption information and related personal goals. The effectiveness of social sharing has been linked to the degree of the target consumer’s connectivity within the social sharing network [88]; specifically, the more connected one is to the social sharing network, the more effective public feedback will be. Relatedly, Gabrielli et al. [33] found users reluctant to share personal data with strangers in the context of mobile apps promoting sustainable travel behavior, i.e., publicness was not appreciated when there was a low level of network connectedness.

3.3.2.2. Response requirement. Accessibility also relates to the response required for user(s) to access the eco-feedback. In general, the easier the access the more likely users will attend to the feedback. For example, Erickson et al. [89] found that the biggest barrier to access in their residential electricity feedback program was the website log-in requirements (ID and password). Ambient eco-feedback comes to mind when considering minimal user response requirement; however, large public displays (e.g., [61]), and push notifications on personal electronic interfaces can also minimize response requirement [90].

3.3.2.3. Location. Accessibility also involves the location of the display, assuming a given medium. For example, a tablet or dedicated IHD could be strategically affixed to an entryway or common room wall (location) to afford easy access for building occupants. In contrast, a household electricity meter is normally out of sight and inconvenient to access [2]. Fitzpatrick and Smith [10] found that users preferred a central location/device to provide energy feedback rather than appliance-specific monitors located on plugs (i.e., load monitors), which were difficult to access and see. Portable IHDs and similar devices can be moved by users to more or less accessible locations [91,92]. Feedback integrated into displays on appliances, i.e., embedded displays [6], are easily accessed at the time of relevant behaviors, and enable strategic timing of feedback presentation.

4. Conclusion

In sum, we identified 15 eco-feedback design dimensions, which fall into three categories: information, timing, and display. Their behavioral implications can be understood in terms of three general behavioral mechanisms: attention, learning, and motivation, which are supported by three corresponding eco-feedback meta-qualities: salience, precision, and meaning. Eco-feedback that is salient promotes attention. Eco-feedback that is precise promotes learning. And eco-feedback that is meaningful promotes motivation.

This study is the most comprehensive review of behaviorally-relevant eco-feedback design dimensions to-date. It is the first to systematically map design dimensions on to behavioral mechanisms. In some cases, the theoretical claims in this paper that certain design dimensions relate to the general behavioral mechanisms of attention, learning, and motivation warrant further empirical investigation. This framework is intended as a point of departure for further study rather than a final set of guidelines. New behaviorally-relevant design dimensions will undoubtedly emerge with the continued emergence of new technical possibilities, and any framework should remain flexible to include these innovations. Table 2 shows potential areas for future research to continue building knowledge regarding each identified eco-feedback design dimension.

The framework can be used by designers as a guide to creating more effective eco-feedback. To begin, the designer(s) should consider (and empirically study) the target user(s)’s baseline performance and levels of awareness, knowledge, and motivation with respect to the target behaviors. If motivation is high, but knowledge is low, it will be especially important to consider design dimensions related to learning. If knowledge is high, but motivation is low, dimensions related to motivation will be most important to consider. If users are motivated and knowledgeable, but lack awareness (i.e., they know what to do and want to do it, but forget), dimensions related to attention would be critical.

Considering all 15 dimensions in the context of any given project is also a useful exercise and will often be necessary when targeting groups of users with diverse behaviors and levels of awareness, knowledge, and motivation. There may also be tradeoffs to consider. For example, if the targeted users are a cohesive social group who would be motivated to engage in feedback reflecting group-level goals, providing collective feedback (low behavioral granularity) rather than individual level feedback (higher behavioral granularity) might be worth sacrifices in the feedback's capacity to support learning; the designer might in turn increase data and temporal granularity, minimize latency, and supplement feedback with an educational program.

Eco-feedback interfaces can be quite complex, with multiple interface elements conveying different information in different ways. For example, an energy dashboard may have a weekly leaderboard conveying relative energy savings of multiple groups, real-time power demand statistics disaggregated to the appliance level, and a line graph showing a long history of energy consumption. The ways in which multiple feedback streams [13] interact is beyond the scope of this paper, but further research should explore how multiple feedback streams complement each other or lead to information overload.

We did not consider dimensions of the back-end technologies, e.g., data source or monitoring approach, that enable the front-end user interface. Though data source may have an effect on consumer behavior via trust in the eco-feedback data [27,6], we focused on the direct effects of the eco-feedback user interface. We also did not account for other aspects of eco-feedback interventions beyond the feedback interface. For example, other research has demonstrated relationships between the length of time an eco-feedback intervention is implemented and its effectiveness [5,93]. Additionally, combining eco-feedback with other strategies, e.g., goal-setting, commitment, education, prompts, incentives, and behavioral consequences (i.e., rewards), has been repeatedly demonstrated as more effective than feedback alone (e.g., [3,5]).

We hope this framework will guide the design of more behavior-centered eco-feedback technologies that will be effective in mitigating the negative environmental impacts of unsustainable resource consumption. We also aspire to stimulate more systematic research regarding the behavioral implications of eco-feedback design dimensions.

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