# Unlocking the Expressivity of Point Lights

**Chris Harrison**[1] **John Horstman**[1] **Gary Hsieh**[2] **Scott E. Hudson**[1]

[1]Human-Computer Interaction Institute
Carnegie Mellon University
5000 Forbes Ave. Pittsburgh, PA 15213
{chris.harrison, scott.hudson}@cs.cmu.edu
john@johnhorstman.com

[2]College of Communication
Arts and Sciences
Michigan State University
East Lansing, MI
garyh@msu.edu

## ABSTRACT

Small point lights (e.g., LEDs) are used as indicators in a wide variety of devices today, from digital watches and toasters, to washing machines and desktop computers. Although exceedingly simple in their output – varying light intensity over time – their design space can be rich. Unfortunately, a survey of contemporary uses revealed that the vocabulary of lighting expression in popular use today is small, fairly unimaginative, and generally ambiguous in meaning. In this paper, we work through a structured design process that points the way towards a much richer set of expressive forms and more effective communication for this very simple medium. In this process, we make use of five different data gathering and evaluation components to leverage the knowledge, opinions and expertise of people outside our team. Our work starts by considering *what* information is typically conveyed in this medium. We go on to consider potential expressive forms – *how* information might be conveyed. We iteratively refine and expand these sets, concluding with ideas gathered from a panel of designers. Our final step was to make use of thousands of human judgments, gathered in a crowd-sourced fashion (265 participants), to measure the suitability of different expressive forms for conveying different information content. This results in a set of recommended light behaviors that mobile devices, such as smartphones, could readily employ.

### Author Keywords

Light behavior; pixels; mobile devices; man-machine communication; crowd-sourced evaluation; indicator lights; LED; expressive; notification.

### ACM Classification Keywords

H.5.2 [Information interfaces and presentation]: User Interfaces - Graphical user interfaces; B.4.2 [Input/Output and Data Communications]: Input/Output Devices - Image Display.


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## INTRODUCTION

Since the advent of the electronic age, devices have incorporated small point lights for communication purposes. This has afforded devices a simple, but reliable communication channel without the complication or expense of e.g., a screen. For example, a simple light can let a user know their stove is on, a car door is ajar, the alarm system is active, or that a battery has finished charging. The development of commercially viable light emitting diodes (LEDs) in the 1970s greatly expanded their penetration and use. Low cost, small size, durability, and remarkable power efficiency has enabled their integration into almost every class of electronic device (Figure 1).

For simplicity, we consider a point light source to be a small, single color light emitting element with an intensity that can be varied over time (e.g., an LED or small incandescent bulb). Although comparatively simple (and inherently one-dimensional), with good design, point lights can be quite expressive. With multiple lights and colors, the design space could be even richer. However, cultural color connotations must be weighed, potentially reducing generality. Context is also important to consider when users are interpreting iconic elements. In this paper, we start with the most severe constraints to demonstrate the potential lower bound richness.

Unfortunately, very few products seem to take full advantage of the expressive capability simple lights can provide. The most commonly encountered *light behaviors* [25] are quite simple: light on, light off, and light blinking. Not only is this vocabulary incredibly small, but the behaviors are not particularly iconic (e.g., what does a blinking light on a toaster mean? Is the toast done? Is it cooking? Is it jammed?). This often means people have to learn by rote what each light behavior means on each device. This is unwieldy given the multitude of devices we use today.

In this work, we hope to reignite people's imagination by demonstrating the impressive and largely unrealized richness of point lights, and their utility in ever-more capable modern electronic devices. Armed with this knowledge, we hope that improved devices - that remain simple, but communicate better - can be built.

To do this, we systematically explore *what* kinds of information are typically being communicated by point lights in


**Figure 1. Small, single color lights have been a persistent feature in electronic and computing devices, from the earliest computers (UNIVAC c. 1951, top left) to modern handheld devices (Android smartphone c. 2011, top right).**

a wide range of commonplace devices - we call these *informational states*. We then turn to *how* both contemporary and future devices might express this information in a point light medium. This results in a substantial set of potentially useful expressive forms – or *light behaviors*.

Finally, we use a crowd-sourced evaluation approach to measure the properties of a candidate set of 24 *light behaviors* with respect to a set of *informational states* that might be used in a mobile device (our proof-of-concept domain). Data from our 265 participants shows that light behaviors vary in their ability to induce consistent interpretations of a particular informational state. Many behaviors perform strongly; of these, we found eight to be *iconic,* in the sense that they strongly and consistently induce a single interpretation (i.e., we expect they would require little or no memorization). Based on our exploration and evaluation, we recommend this set for use in mobile devices, such as smartphones.

## RELATED WORK

Iconic forms have been used since the beginning of interfaces because, when successful, they can consistently convey a meaning to users. This allows people to work more by *recognition* and less by *recall*. There is a substantial body of work on icon design that we will not review here (see for example [4,10,22]). In addition to conventional visual forms, iconographic entities can be created in auditory [5,7,12,13,14], vibro-tactile [6,11] and even textural forms [15]. As recently considered by [16], this concept can also be expanded to include forms that geometrically manipulate visual icons and elements over time.

Single point lights are, by their nature, limited in their expressive power (when e.g., compared to computer screens, which contain what amounts to millions of full-color point lights capable of rendering graphics). One reason for this is that point lights are both *sequential* and *non-persistent* [20]. That is, to convey a meaning, light behaviors normally must be presented via a particular ordered progression of intensities and then disappear after they are delivered. Thus, they must either be remembered by the user or repeated. This property is fundamentally different from typical (non-animated) visual displays in graphical interfaces [10, 22], where the user can randomly access persistent information as they see fit by looking at different parts of the display.

This sequential and non-persistent property is shared by a number of other media types, including audio, speech and most uses of haptics. Because of this commonality, it is likely that some of the techniques originally designed in these domains, might eventually be found to be useful for light behaviors as well (e.g., the kind for rapid skipping forwards or backwards through otherwise long audio prompts used in [3]).

There is also considerable literature on *ambient* displays, which considers approaches intended to convey limited amounts of information in a lightweight fashion [23,24,29], for e.g., the purpose of reducing human attention demand. Approaches are numerous and diverse. Those most similar to our work are those that employ dynamic visual output as their communication channel. For example, information-enriched art that could be hung on a wall [17], a LED-studded bracelet that fosters social awareness [32], a water lamp that projects ripples as digital bits rain down [9], and shoes that glow or flash in response to social [8] or personal informatics [21].

In work more directly related to this paper, Pintus introduces the concept of light behaviors that we have adopted here. In [25], it is introduced as "[giving] a concrete representation of the intangible and invisible events that are taking place [in a device]." A small design exercise centered on wireless communication between two devices suggests two light behaviors - one for connection and one for file exchange. Also, Wessolek describes a method for authoring "one pixel displays" by taking sound recordings, and mapping the amplitude to illumination intensity (e.g., an audio snippet of a heart beat or sea shore) [30,31]. Finally, [28] described the construction and use of an audio- and vibration-sensitive device designed to exhibit a range of expressive light behaviors for e.g., theatrical performances.

## FORMATIVE EXPLORATIONS

In this paper, we work through a structured design process to uncover and then evaluate new and useful *light behaviors*. In this process, we used five different data gathering and evaluation components, each tuned to a particular phase of the work. This approach allowed us to leverage the knowledge, opinions and expertise of groups of people outside of our team, in a range of ways that were appropriate to the different phases of our investigation.

In the overall process, we first sought to identify contemporary uses of point lights – both where and how they are used. We then iteratively refine our findings and produce a set of candidate designs. Finally, we use human judgments gathered in a crowd-sourced fashion to measure the suitability of different expressive forms for conveying different information content.

To begin this work, we had to establish two fundamental lists. The first is a list of *what* information various devices might want to communicate to users. For example, that a mobile phone is low on batteries, that an oven has reached the desired temperature, or that an external drive is transferring data. We call these *informational states*, or *states* for short.

The second list is *how* devices communicate these states to users using point lights. A progression of illumination intensities over time is called a *light behavior*. A sinusoidal fading in and out would be one example of a light behavior; another would be a blinking sequence using the SOS pattern.

Finally, we note that, for brevity, we use the term *device*. However, this should be read to encompass a variety of electronic and computational objects, from something as small as a digital watch, all the way up to an automobile.

### Initial Exploration

To help ground our earliest explorations and seed our own intuitions, we selected and informally studied a small set of commonplace devices that incorporated point lights with expressive behaviors (3 people considered 27 devices over a two week period). To give a flavor of what we found, we describe three examples of current design practice.

The first of these is a Philips Sonicare electric toothbrush (Figure 1, lower right). This features a single green light on the handle of the device. The toothbrush exhibits four light behaviors. 1) When fully charged and situated in the recharging dock, the light is on and solid. 2) When out of the dock and with sufficient charge (including when in use), the light is off. 3) When running low on batteries, the light blinks at approximately 6Hz. 4) When recharging in the dock, a 1Hz blink is displayed.

Next, we look at an Apple MacBook laptop (Figure 1, bottom left; Late 2008 aluminum unibody model), which incorporates a single white light on the front bezel. Apple is widely credited with bringing the “breathing” light behavior (i.e., a smooth fading in and out) to popular use [18]. This occurs when the computer is in sleep mode. Two other light behaviors are used: 1) when the computer is on, the light is off (which, interestingly is opposite most other devices); and 2) when the computer is first turned on, the light fades on, stays lit for roughly four seconds, and then fades off.

Lastly, we examine a T-Mobile Comet (2011) Android 2.2 smartphone (Figure 1, top right). In our informal investigation, this was a user’s primary phone and loaded with popular applications. In practice, it appears very few light behaviors are employed. This is because the single integrated LED is reserved for alerting the user to notifications (i.e., items that appear in the Android OS notification pull-down menu), which in turn, tend to use the OS-defined default 0.3Hz blinking light.

Of note, the Android API allows for applications to define their own notification light behavior. There are three parameters: the color of the light, the on duration, and the off duration [2]. For example, the Facebook Android application uses the same 0.3Hz blinking light behavior for its notifications, but with a blue light instead of the default green. While providing some level of programmatic control, the API actually precludes most of the rich light behaviors we introduce later – designers are limited to simple on/off blinking patterns, which are not particularly expressive or iconic (e.g., even a SOS or increasing frequency pattern is not possible).

The three examples we introduced here, while obviously a very small set of all possible devices, are indicative of current uses for point lights and their expressive behaviors (see also [4,26] for more real-world examples). In fact, of the dozens of devices we looked at, these three examples offered what we believed were some of the better light behavior sets. Most other devices we surveyed were far less sophisticated in their design and use of point lights.

These experiences and devices were drawn from the small circle of the authors. To put our data on firmer footing, we expanded our scope, reaching out to a wider audience, and more systematically gathering data about current uses of point light sources. We now describe these stages of our investigation.

### Survey 1: Where are Point Lights Used?

To expand our understanding, we created an online survey, asking 27 participants (15 female, mean age 32.0) to “list up to 15 devices, appliances or objects [they] regularly encounter that feature one or more small lights.”

Respondents provided 247 answers, yielding 77 unique devices. Data is summarized in Figure 2. Above all else, this demonstrated the impressive breadth of point light use

– what seemed to be almost every electronic device in the home and office. The top ten most popular responses were computer (28; laptop/desktop/undefined combined), modem/router/hub (20), television (17), mobile phone (16), car (13), monitor (10), coffeemaker (8), alarm clock (7), DVD player (7), and oven (7).

### Survey 2: How are Point Lights Used?

Using the top ten responses from Study 1, we created a second online survey that sought to collect *how* point lights were used in commercial devices and what information users believed they were conveying.

Specifically, we asked 13 participants (4 female, mean age 27.6) to describe as many light behaviors they could view or recall for each of the ten devices (if owned). Further, we asked them to explain *what* they believed each behavior was attempting to communicate. For example, *light fading in and out* is communicating that the *laptop is sleeping*.

Survey results suggested most devices employed an extremely small number of light behaviors (3.8 on average, SD=1.1, including light off as one mode). The most pervasive behaviors were light on (i.e., solid), light dim, light off, light blinking, and light fading in and out. Interestingly, few participants gave details on the types of blinking or fading – drawing no real distinctions between e.g., different frequencies, patterns or intensities.

Further, likely in response to the limited vocabulary of light behaviors, devices tended to convey an equally small number of informational states. For example, a TV might have light off = TV off, light on = TV on, light blinks = TV received command from remote.

Mobile phones had the richest light behavior set (6 unique responses) and informational states (17 unique responses). We found this disparity in number of *behaviors* and *states* intriguing – it seemed mobile phones could convey so much more if only they were equipped with a richer set of light behaviors. In response, we decided to set mobile device as our proof-of-concept domain for later in-depth investigations.

### Design Session: Exploring the Space of Expressions

Next, we solicited help from a panel of ten designers (recruited from a professional graduate program at our university; 3 female, mean age 25.9). We conducted an in-person Design Session lasting 60 minutes. The session started by asking the designers to individually generate as many light behaviors as possible. In hopes of stimulating new behavior designs, we imposed no constraints, beside the fact lights had to be a single color and point sources. After five minutes, these were shared by going around the table. In total, 34 unique light behaviors were enumerated.

We then asked the designers to individually brainstorm informational states a smartphone might want to communicate to a user. After five minutes, they were asked to share their ideas. Once an idea was read, a corresponding post-it note was stuck to a large whiteboard. After all the ideas had been read (44 unique items), they were tasked with organizing them into an affinity diagram. The result was nine high-level groupings: “don’t be late”, “informative”, “something nearby”, “resource availability”, “device status”, “response needed”, “notification”, and “biofeedback”.

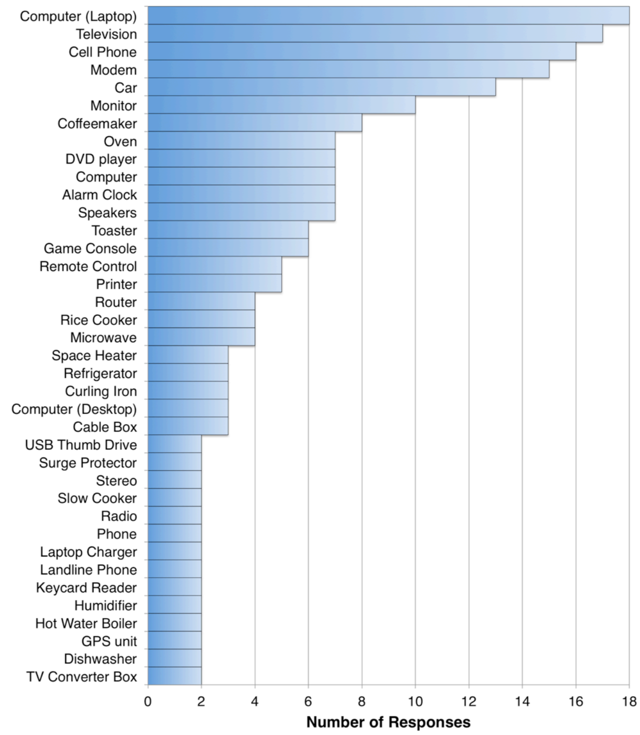


**Figure 2. Response histogram from Study 1. Not shown here are 38 other devices that had single responses.**

### Consolidation

Using data from Survey 2 and the Design Session, we formulated a prototype vocabulary of light behaviors. There was no light behavior we encountered our Initial Exploration that was not represented in this final set. This partially served as confirmation that Survey 2 and the Design Session were successful at enumerating new and existing designs. We dropped designs that were ill-defined or challenging to recreate in point light form (e.g., “copy machine light”, “fireworks”). Also, designs that were very similar were combined (e.g., “wave”, “breath in/out”). In total, we created 24 light behaviors, illustrated in Figure 4 (see also Video Appendix).

Additionally, we selected 12 informational states for our experimental set. These had to be clearly defined and in popular use today (e.g., “incoming call”, and not “caloric intake exceeded”). While not exhaustive, it gave us a compact, high quality list we could use for study purposes:

1. The device has an incoming call.
2. The device has received a message.
3. The device is notifying the user about an event or scheduled item.
4. The device is notifying the user about the current location.

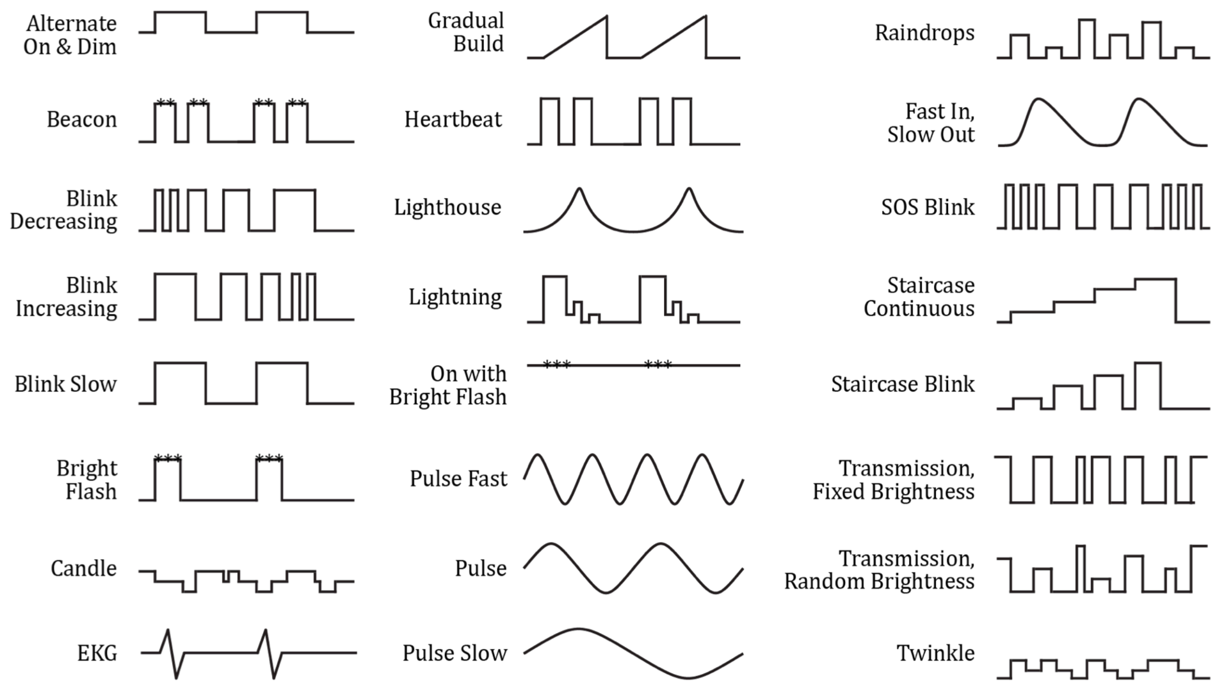


**Figure 3. Sparklines representing the illumination intensity over time for our 24 proof-of-concept light behaviors. Intensity ranges from off (Figure 4A) to high (Figure 4C). Asterisks imply the extra bright "flash" conditions shown in Figure 4D (e.g., at the tops of the pulses in Bright Flash).**

5. The device has low battery.
6. The device is thinking, computing, or processing.
7. The device is sleeping, suspended, or hibernating.
8. The device is turning on, booting, or warming up.
9. The device is transmitting or receiving data.
10. The device is unable to connect.
11. The device is unable to accept user input or commands.
12. The device is active, monitoring, running fine, or progressing.

During piloting, we found participants struggled with item 4 (which was derived from the "something nearby" affinity grouping). Think-alouds revealed people were generally unfamiliar the concept of geo-spatially-driven notifications (which while popular in research systems, has yet to gain traction with everyday users). In response, item 4 was dropped, leaving 11 states, which piloted well.

## FROM LIGHT BEHAVIORS TO MEANINGS

Our formative explorations yielded a list of 24 light behaviors and 11 informational states. However, what was unknown was how these light behaviors mapped to informational states, if at all. We now describe the study we used to establish and evaluate these mappings. The results allow us to recommend a set of *behaviors* that strongly and iconically map to *states*, and could be immediately employed in today's mobile devices.

### Procedure

Using a generic smartphone form (Figure 4), we created animations for each of our 24 light behaviors (Figure 3 and Video Appendix). These were exported as animated GIFs, which could be easily embedded into our web-based study.

Participants in our study were shown ten random light behaviors, one at a time, and asked to "rate how strongly [they] agree or disagree with each of the following interpretations about the state of the device". A five-point Likert scale was provided next to each of the 11 states (ranging from 1, strongly disagree, up to 5, strongly agree). After the ten light behaviors had been rated with respect to each *informational state*, a brief demographics survey was administered.

### Participants

To make claims about the generality and iconic-ness of light behaviors, it was important to recruit a large and diverse set of study participants. To achieve this, we used a crowd-sourced approach employing Amazon's Mechanical Turk [1] to recruit participants. Table 1 provides a demographics breakdown.

Our study was limited to workers from the United States, who had submitted at least one unit of work on Mechanical Turk and had an approval rate of 80%. This was to ensure our participants had basic English language proficiencies and to minimize low-quality workers. 302 participants (workers) completed our study and were paid $1.50.

To ensure a high level of answer integrity, we instituted three reliability checks (see [27] for additional approaches to reliability in crowd sourced studies). Foremost, partici-

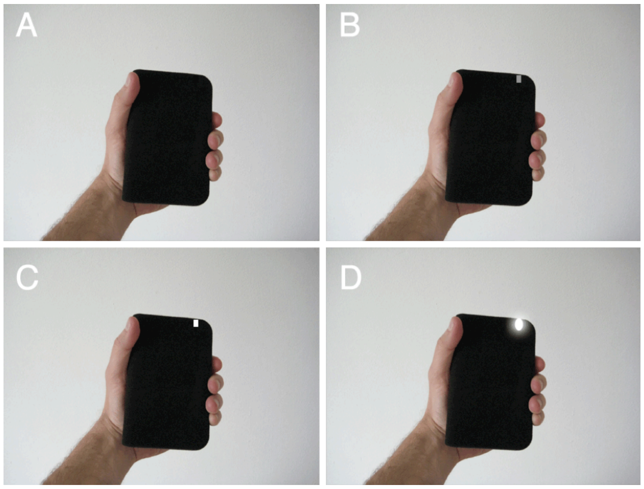


**Figure 4. We placed a virtual LED on a generic smartphone. Illumination intensity was continuous from off (A) through dim (B) to high (C). A separate extra bright "flash" state was also included (D; asterisks in Figure 3).**

pants were dropped if their answers had near-zero variances (e.g., all 3's). Second, participants who completed the study too quickly were also removed. Finally, in two of the ten light behaviors, we duplicated one item rating (e.g., "the device has low battery" rating appeared twice). If a participant's rating differed by more than one Likert point, their data was discarded. In total, this process removed 37 participants, leaving data from 265 participants (156 female, median age between 25 and 30).

Following what has been reported by others recently (e.g., [16,19]), use of a crowd-sourced approach for this process is powerful. Because this part of our investigation could be situated as a small and simple rating task, it was suitable for simple deployment to a crowd sourcing service. This in turn allowed us to rapidly and inexpensively gather information from many more subjects than would have been practical using other approaches.

Finally, it is important to note that participants are likely heavily influenced by light behaviors they have already encountered, and may even see on daily basis. There is no way to effectively control for this, and in fact, it would be ecologically invalid to do so. The reality is users have integrated current design practice into their "device language" and future designs need to build on top of this knowledge, not ignore or disregard it.

## RESULTS

All 24 of our light behaviors conveyed some informational states better than others (one-way ANOVA on each behavior, $p<.05$). This shows that light can be expressive and convey different information dimensions. Figure 5 provides an overview of the study results.

### Dimensions of Informational State

We ran a factor analysis on the ratings of our 11 informational states (Maximum Likelihood, Varimax rotation). The

| Gender | % |
|---|---|
| Male | 39 |
| Female | 61 |

| Age | % |
|---|---|
| 18-24 | 23 |
| 25-30 | 30 |
| 31-40 | 19 |
| 41-50 | 15 |
| 51+ | 13 |

| Salary | % |
|---|---|
| <$20k | 33 |
| $20k-30k | 22 |
| $30k-$50k | 22 |
| $50k-$75k | 11 |
| $75k+ | 12 |

| Education Level | % |
|---|---|
| Some high school | 2 |
| High school diploma | 11 |
| Some college | 29 |
| Associate Degree | 7 |
| Bachelor Degree | 36 |
| Advanced Degree | 15 |
| Other | 0 |

| Daily Comp. Use | % |
|---|---|
| <1 hr | 1 |
| 2-3 hr | 22 |
| 4-6 hr | 27 |
| 6-10 hr | 35 |
| > 10 hr | 15 |

**Table 1. The demographics of our Mech. Turk Participants**

analysis revealed several states were highly correlated, and that the data had five underlying dimensions (confirmatory factor analysis; $p<.001$). These clustered in a conceptually logical way, suggesting five higher-level *informational categories*, described in Table 2.

For example, "*device has an incoming call*", "*device has received a message*", and "*device is notifying the user about an event or scheduled item*" were all highly correlated with one another. These all have a similar notification connotation, and thus we place them under a notification *informational category*. We use these high-level categories for the remaining analysis. Figures 6 through 10 show the same data as Figure 5, but organized by informational category and sorted by average rating.

This analysis reveals an important design implication. Specifically, it suggests our 24 light behaviors may not be (without user learning) rich enough to convey a distinction between particular types of notification - for example, the difference between a call and text message. However, our behaviors can clearly convey notifications as something different from e.g., turning on. In other words, our behavior

| Factor | Category | Informational States |
|---|---|---|
| 1 | Notification | The device has an incoming call.<br>…received a message.<br>…event or scheduled item. |
| 2 | Active | …transmitting or receiving data.<br>…thinking, computing, or processing.<br>…active, monitoring, … or progressing. |
| 3 | Unable | …unable to connect.<br>…unable to accept user input or commands. |
| 4 | Low-Energy State | …low battery.<br>…sleeping, suspended, or hibernating. |
| 5 | Turning On | …turning on, booting, or warming up. |

**Table 2. A factor analysis indicated there were only five underlying dimensions in the informational states we selected for the study. We suggest five high-level category names for these factors.**

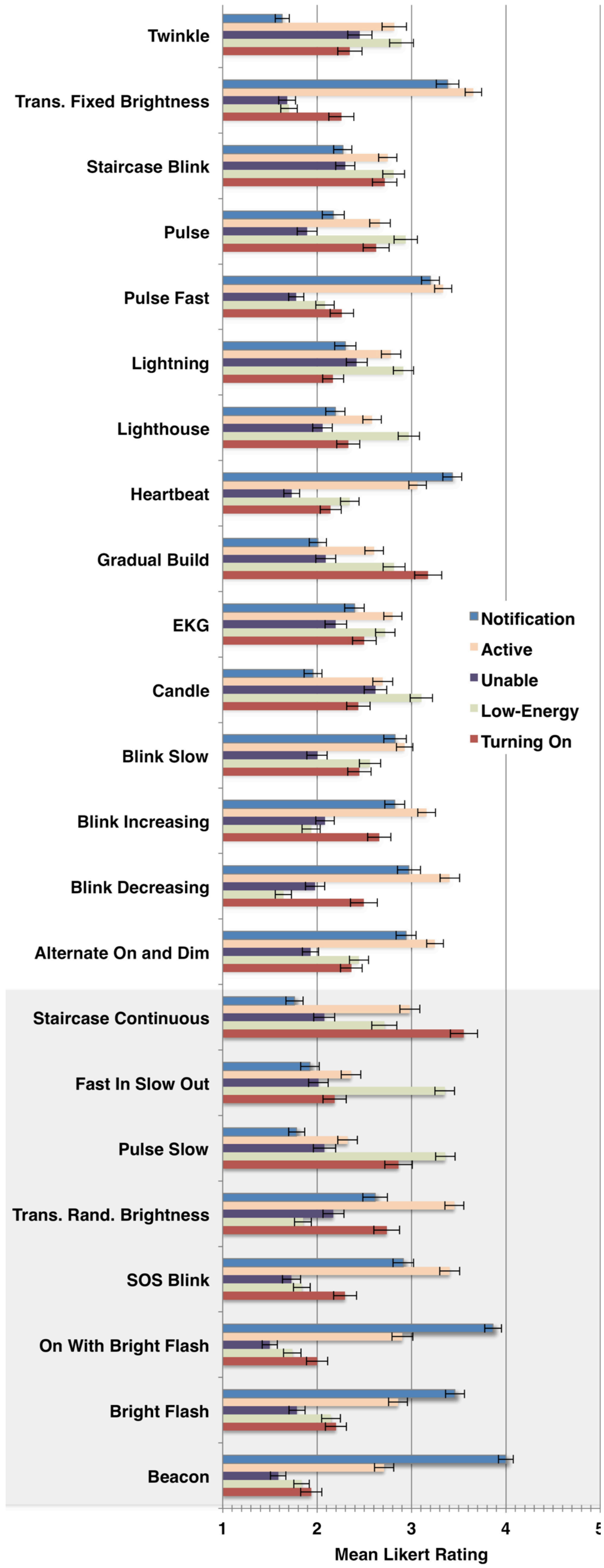


**Figure 5. Basic results of our evaluation; average rating of each light behavior in indicating each informational category.**

set likely has the ability to convey different category connotations, but not informational states within-categories.

## Light Behaviors

Light behaviors lie along a continuum of interpretation strength, without an innate threshold for what is a good or bad behavior (see e.g., Figure 6). For our analysis, we define good light behaviors as those that meet two criteria: 1) it must have a *strong* interpretation (i.e., mean Likert ratings in the top quartile), and 2) it has to be *iconic* – that is, it has one dominant interpretation (significantly so). For example, a light behavior that has both strong *notification* and *active* interpretations is less desirable because it is ambiguous (see e.g., *Pulse Fast* in Figure 5).

To assess iconic-ness, we used a mixed model analysis of variance. We divided our dataset into the aforementioned five categories of states. For each category, participant's rating was the dependent variable and the light behaviors were the predictor variables. Because each participant rated 10 random light behaviors, we also modeled light behavior-id nested within participant as a random effect. The models were all significant, indicating that within each category, there were significant differences across ratings. To determine which lighting behavior(s) best represented each category, we conducted post-hoc tests using Tukey's HSD.

Eight light behaviors met both of our criteria - strong and iconic - and form our recommended light behavior vocabulary (Figure 5, shaded area). We now describe the best performing light behaviors in the context of our five informational categories.

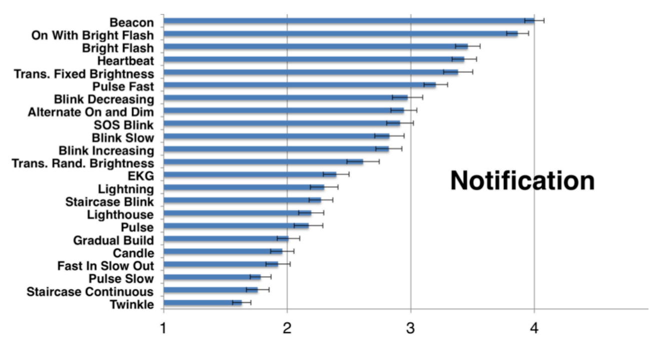


**Figure 6. Ratings of light behaviors in indicating the notification category.**

### *Notification Category*

Three light behaviors are iconic for notifications: *Beacon*, *Bright Flash* and *On with Bright Flash*; all other item interpretations are rated significantly lower ($p<.05$). These are also the top three highest rated behaviors in the notification category (mean Likert scores of 4.0, 3.9 and 3.5 respectively, see Figure 6). *Beacon* is particularly strong, significantly outperforming 22 other behaviors (all except *Bright Flash*; Tukey's HSD, $p<.05$). The commonality between these three behaviors is straightforward – they all feature sharp and rapid bursts of maximum intensity light.

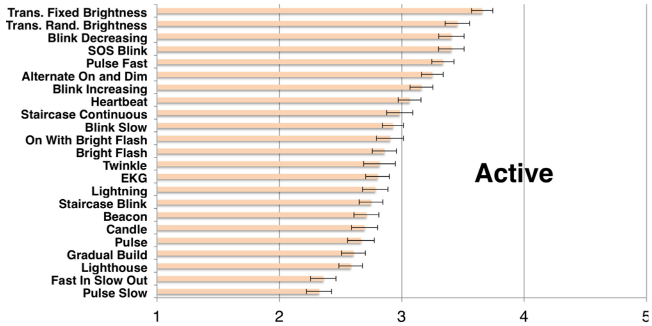


**Figure 7. Ratings of light behaviors in indicating the active category.**

*Active Category*

*SOS Blink* and *Transmission Random Brightness* are both iconic in the active category (p<.05 against all other interpretations). These are the second (mean=3.5) and fourth (mean=3.4) highest rated behaviors in the active category (Figure 7).

Of note, the top rated behavior was *Transmission Fixed Brightness* (mean=3.7), which has an identical temporal pattern to *Transmission Random Brightness*, but with a fixed level of brightness (see Figure 3). The fixed intensity version, however, simultaneously invoked strong notification connotations (Figure 5; difference p<.05). This serves an excellent example of how even subtle features of a light behavior can dramatically impact its interpretation, for example, altering its meaning or making it ambiguous.

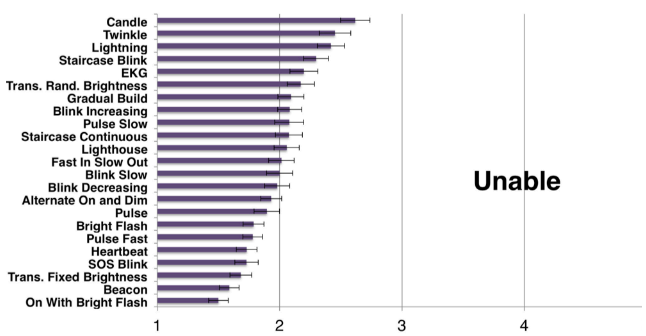


**Figure 8. Ratings of light behaviors in indicating the unable category.**

*Unable Category*

No light behaviors we tested rate highly in the unable informational category (consisting of "*the device is unable to connect*" and "*the device is unable to accept user input or commands*" states). The highest rated behavior, *candle*, has a mean of only 2.6. While it is possible we simply did not include a light behavior that conveyed an unable connotation, and others may be able to find one, we believe the consistently low rating across all 24 behaviors is suggestive that unable-like states may just be difficult to convey with light alone, or is an ill-defined informational category.

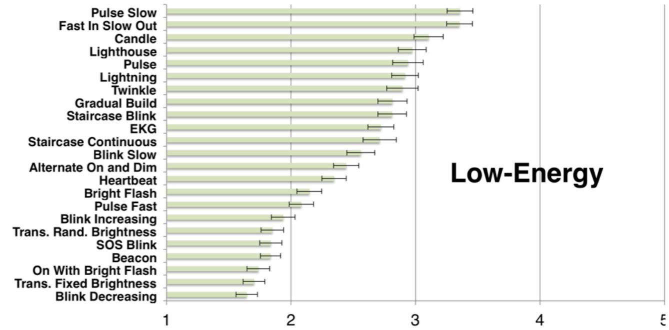


**Figure 9. Ratings of light behaviors in indicating the low-energy state category.**

*Low-Energy State Category*

Two behaviors are iconic in this category: *Pulse Slow* and *Fast In Slow Out* (p<.05 against all other informational categories). They are also the two highest rated, both with a mean Likert score of 3.4 (Figure 9). These are conceptually very similar – long, drawn out fade sequences, similar to restful breathing. This is the "sleeping" light behavior that has been popularized by Apple products.

We included two additional fading light behaviors, *Pulse* and *Pulse Fast*, in order to investigate how pulse frequency affects their connotation. Interestingly, and somewhat expectedly, as pulse frequency increases, ratings for low power state decrease (see Figure 9, *Pulse Slow*, *Pulse*, and *Pulse Fast*). Inversely, average ratings for notification and active categories increase. Put simply, it appears the more motion and activity there is in the light, the more energy it conveys, which is linked to e.g., notifications and processing more than e.g., running out of batteries or hibernating, which are conceptually linked with reduced energy.

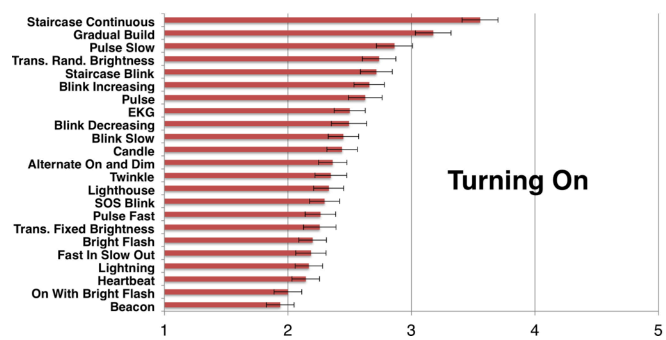


**Figure 10. Ratings of light behaviors in indicating the turning on category.**

*Turning On*

The "*device is turning on, booting, or warming up*" informational state was found to be a unique dimension in participants' ratings. It is a very well defined state of a device, and similarly, participants had decisive reactions to which light behaviors were associated with it (Figure 10).

One behavior stood out - *Staircase Continuous* – which is both the top rated behavior and iconic ($p<.05$ against all other informational categories). Moreover, it significantly outperforms 22 other behaviors (all except *Gradual Build*; Tukey's HSD, $p<.05$).

## DISCUSSION

Based on our findings, we can recommend eight of the light behaviors that emerged from our multi-stage design process for mobile device use (see Figures 4 and 5, shaded area). For providing a notification, we can recommend the *Beacon*, *Bright Flash*, and *On with Bright Flash* behaviors. For the informational states matching the Active category, we can recommend *Transmission Random Brightness* and *SOS Blink* behaviors. For an indication of a Low Energy State, we can recommend the *Pulse Slow* and *Fast In Slow Out* light behaviors. Finally, for conveying that a device is turning on, we can recommend the *Staircase Continuous* behavior. None of the light behaviors we developed and evaluated can be recommended for the Unable category of information states.

In regards to design, our experience with e.g., the difference between the *Transmission Fixed Brightness* and *Transmission Random Brightness* provides a note of caution. As is often the case in display and interaction design, some seemingly small differences can have large and/or unexpected effects, while most remain simply small differences. Telling these apart typically requires user testing and evaluation, one form of which we have illustrated in this work.

## CONCLUSION AND FUTURE WORK

In this paper, we have considered how point lights found in a wide array of current devices might be made more expressive. Contemporary uses are generally simple, and in many respects, unnecessarily limited. We worked through a structured design process that involves multiple data gathering and evaluation steps, which allowed us to leverage the knowledge, opinions and expertise of people outside our team in a range of ways. Our final design stage solicited interpretation ratings from 265 participants, representing a wide range of demographics. From this process, we have been able to evaluate 24 different light behaviors, eight of which we recommend for use in a mobile device domain.

We should also note that while we believe the design and evaluation process presented here provides recommendations that are generally useful, the evaluations are clearly far from exhaustive in the factors that could be considered. In particular, there are many contextual factors that are particular to specific devices and circumstances that have not been brought into consideration. Further, the effectiveness of a light behavior can be heavily influenced by other displays found nearby, by learned conventions that users bring from other devices, and varying judgments of illumination magnitude due to dynamic environmental conditions, among many factors. Nonetheless, we do believe this work is useful starting point, and importantly, demonstrates the immediate possibilities in the domain.

There are many directions in which this work could be extended in the future. Foremost, we narrowed in on mobile devices as our proof-of-concept domain. However, there are many other classes of device that would benefit from tailored light behavior sets. How groups of devices employing rich light behaviors function in concert is unknown. It is possible a "light vocabulary" could emerge in a similar way as isotypes have become universal.

The process used in this work should provide a useful template for future evaluations. There are undoubtedly light behavior designs that we did not evaluate that might provide strong and iconic indications of a particular informational state. Additionally, the list of informational states of e.g., smartphones will continue to expand as their use matures. It would be interesting to explore how many unique dimensions point lights could convey effectively.

Finally, it is easy to imagine expanding this work to encompass lights with varying color, size, directionality, diffuseness, and shape. This would dramatically boost their expressive capability, though likely with a corresponding increase in design and evaluation complexity. Moreover, users are influenced by context, potentially influencing the interpretation of an icon (light or otherwise). It remains to be seen how robust light behaviors are across cultures and use scenarios.

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## REFERENCES

1. Amazon Mechanical Turk. http://www.mturk.com
2. Android API, "Adding flashing lights". Retrieved September 13, 2011. http://developer.android.com/ guide/topics/ui/notifiers/notifications.html#Lights.
3. Arons, B. SpeechSkimmer: interactively skimming recorded speech. In *Proc. UIST '93*, 187-196.
4. Baumann, K. and Thomas, B. (2001). *User Interface Design of Electronic Appliances*, 1st Ed. CRC Press.
5. Blattner, M. M., Sumikawa, D. A., and Greenberg, R. M. Earcons and icons: their structure and common design principles. *Human-Comp. Inter.* 4, 1 (1989), 11-44.
6. Brewster, S. and Brown, L. M. Tactons: structured tactile messages for non-visual information display. In *Proc. Australasian User Interface '04*. 15-23.
7. Brewster, S. A., Wright, P. C. and Edwards, A. An evaluation of earcons for use in auditory human-computer interfaces. In *Proc. CHI '93*. 222-227.

8. Chen, C., Forlizzi, J., and Jennings, P. ComSlipper: an expressive design to support awareness and availability. In *CHI '06 Ext. Abs*. 369-374.
9. Dahley, A., Wisneski, C., and Ishii, H. Water lamp and pinwheels: ambient projection of digital information into architectural space. In *Proc. CHI '98*. 269-270.
10. Easterby, R. The Perception of Symbols for Machine Displays. *Ergonomics* 13, 1 (1970), 149-158.
11. Enriquez, M. J. and MacLean, K. E. The Hapticon Editor: A Tool in Support of Haptic Communication Research. In *Proc. HAPTICS '03*. 356-362.
12. Gaver, W. Auditory Icons: Using Sound in Compute Interfaces. *Human-Comp. Interac.* 2, 2 (1986), 167-177.
13. Gaver, W. The Sonic Finder: An Interface that Uses Auditory Icons. *Human-Computer Interaction*, 4, 1 (1989), 67-94.
14. Hankinson, J. C. and Edwards, A. D. Designing earcons with musical grammars. *SIGCAPH Comput. Phys. Handicap*. 65 (Sep. 1999), 16-20.
15. Harrison, C. and Hudson, S. E. Texture displays: a passive approach to tactile presentation. In *Proc. CHI '09*. 2261-2264.
16. Harrison, C., Hsieh, G., Willis, K. D. D., Forlizzi, J. and Hudson, S. E. Kineticons: using iconographic motion in graphical user interface design. In *Proc. CHI '11*. 1999-2008.
17. Holmquist L. E., and Skog, T. Informative art: information visualization in everyday environments. In *Proc. GRAPHITE '03*. 229-235.
18. Huppi, B. Q., Stringer, C. J., Bell, J. and Capener, C. J. United States Patent 6658577: Breathing status LED indicator, 2003.
19. Kittur, A., Chi, E. H., and Suh, B. Crowdsourcing user studies with Mechanical Turk. In *Proc. CHI '08*. 453-456.
20. Lee, S. H., and Blake, R. Visual form created solely from temporal structure. *Science*, 284 (1999). 1165-1168.
21. Lim, B. Y. Shick, A., Harrison, C., and Hudson, S. E. Pediluma: motivating physical activity through contextual information and social influence. In *Proc. TEI '11*. 173-180.
22. Lodding, K. Iconic Interfacing. *IEEE Computer Graphics and Applications*. 3, 2 (1983), 11-20.
23. MacIntyre, B., Mynatt, E. D., Voida, S., Hansen, K. M, Tullio, J., Corso, G. M., Support for multitasking and background awareness using interactive peripheral displays. In *Proc. UIST '01*. 41-50.
24. Mankoff, J., Dey, A. K., Hsieh, G., Kientz, J., Lederer, S. and Ames. M. Heuristic evaluation of ambient displays. In *Proc. CHI '03*. 169-176.
25. Pintus, A. V. Tangible lightscapes. In *Proc. TEI '10*. 379-380.
26. Pintus, A. V. A collection of light behaviours (video). Retrieved Sept. 7, 2011. http://vimeo.com/8612242
27. Rzeszotarski, J. and Kittur, A., Instrumenting the crowd: Using implicit behavioral measures to predict task performance. In *Proc. UIST '11*. 13-22.
28. Seitinger, S., Taub, D. M. and Taylor, A. S. Light bodies: exploring interactions with responsive lights. In *Proc. TEI '10*. 113-120.
29. Weiser, M. and Brown, J. S. 1997. The coming age of calm technology. In *Beyond Calculation: The Next Fifty Years of Computing*. Denning P. J. and Metcalfe, R. M. (eds), Springer-Verlag. 75-85.
30. Wessolek, D. 2008. Semiotic Foundations of Illuminants as Time-Based Medium in Space: Experiments and Artifacts. MFA Thesis, Bauhaus University Weimar, Germany.
31. Wessolek, D. Bouncing glow: methods of creating content elements for one-pixel-displays. In *Proc. TEI '11*. 443-444.
32. Williams, A., Farnham, S., and Counts, S. Exploring wearable ambient displays for social awareness. In *CHI '06 Ext. Abs*. 1529-1534.