CairnFORM: a Shape-Changing Ring Chart Notifying Renewable Energy Availability in Peripheral Locations

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ABSTRACT
We present CairnFORM, a shape-changing cylindrical display that physicalizes forecasts of renewable energy availability. CairnFORM aims at creating and encouraging new socially-shared practices by displaying energy data in collective and public spaces, such as public places and workplaces. It is 360˚-readable, and as a dynamic physical ring chart, it can change its cylindrical symmetry with quiet motion. We conducted two user studies. The first study clearly revealed the attractiveness of CairnFORM in a public place and its usability for a range task and for a compare task. Consequently, this makes CairnFORM useful to analyze renewable energy availability. The second study revealed that a non-constant motion speed is the better visualization stimulus at a workplace.

Author Keywords
Tangible User Interface; Shape-Changing Interface; Data Physicalization; Ring Chart; Renewable Energy; Demand-Side Management; Shifting Energy Demand; Ambient Notifications; Peripheral Vision; User Study.

INTRODUCTION
Demand-Side Management (DSM) can help to increase the consumption of renewable energy. However, as energy generation shifts to renewables and microgeneration[1], the interplay between energy supply and energy demand becomes more complex to manage. Critical problems, such as peak demand, can lead to power outages and make the electrical grid inefficient [10]. These issues are amplified by the fluctuation of renewable energy generation according to weather conditions (e.g., sun, wind, wave, tide) and by the limitations of energy storage capacities [14]. Unless energy storage becomes economically and environmentally reliable to balance energy supply against energy demand [37], we will need to synchronize energy demand with renewable energy availability. During the last five years, researchers have designed and studied systems to encourage users in using renewable energy. Most of these systems target households. As suggested by Pierce and Paulos [45], we should also design systems for collective or public spaces, as workplaces, cafes, parks, schools, museums, and urban places. These targeted contexts require adapted displays and visualization elements.

[1]Microgeneration is small-scale generation of electricity or heat by individuals, businesses, or communities to meet their own needs.

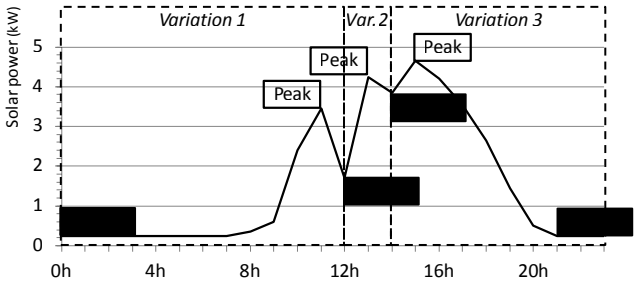


Figure 1: Three variations of solar power generation during a partly cloudy day in summer (produced with a 5 kW installation of photovoltaic panels, on the buildings' roof of our laboratory, on August 26, 2012).

In this paper, we present CairnFORM, a shape-changing cylindrical display that can change cylindrical symmetry. We use CairnFORM as a 360˚-readable, dynamic ring chart that physicalizes renewable energy data in public spaces, such as public places and workplaces.

The remainder of this paper is organized as follows. In the following section, we present the major requirements that lead to the design of a new kind of display. In Section 3, we discuss some solutions from previous work. Then, in Section 4, we describe our CairnFORM shape-changing interface in detail and propose three possible motion speeds to animate it at workplaces. In Section 5, we describe the two user studies that we conducted in order to evaluate CairnFORM and the motion speeds. Then, in Section 6, we outline the contribution of these studies, for both the domains of energy demand-side management and shape-changing interfaces. In Section 7, we discuss the contributions and the limitations of this work. Finally, we conclude and provide directions for future work.

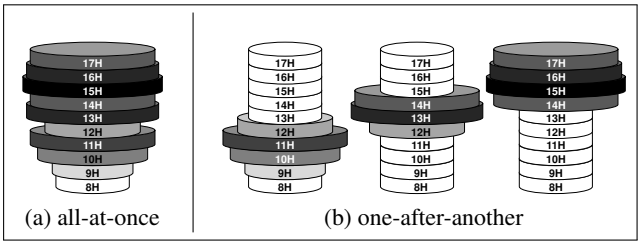
THE DESIGN OF A NEW KIND OF DISPLAY

Using renewable energy rather than non-renewable energy is a strategy considered as appropriate to reduce environmental impact. Over the last five years, interactive systems have been designed to encourage users in using renewable energy when there is plenty of it rather than when there is little (i.e., shifting energy demand) [5,29,44,47,50,53]. Most of these systems target households to plan everyday energy usage (e.g., washing machine, oven, battery charger) by visualizing forecast data of renewable energy production using graphical charts such as clock charts [29,50], timeline charts [50], and line charts [29,53]. But interactive systems will also be useful to shift energy demand in public spaces, especially in microgeneration contexts.

Data physicalizations are growing popular in many societal domains which indicates a strong potential for fostering public engagement [24]. Typical examples of dynamic physicalizations are dynamic physical charts, ranging from line charts[2] to pie charts [49], and to bar charts [55]. These new kind of charts create opportunities to display energy forecasts in public spaces in an engaging way. The tangible representation of energy Watt-I-See [47] is an example of such a public installation.

In order to display energy data in public places and at workplaces, such as open-plans and offices, our viewpoint-independent display can be installed anywhere. The discrete ring structure displays ordinal data: each ring represents the average energy available in one hour. Displaying hourly forecasts[3] aims at, in our use case, providing simple instructions to the users: simple time slots are easier to remember in order to plan energy shifting.

Retrieving variations' peaks is a basic task of energy shifting. An energy variation starts from a minimum energy availability (local minimum or global minimum), increases until a maximum (local maximum or global maximum), and decreases until the following minimum (local minimum or global minimum). Renewable energy production on a day has rarely a single variation; several variations often occur the same day (see the example shown in Figure 1). We understood, thanks to a preliminary user study using charts printed on paper [6], that users struggle in retrieving all the peaks when visualizing variations all-at-once (see Figure 2a). We iterated with three groups of seven participants using a unicolored chart displaying all the variations, a grayscale chart displaying all the variations, and grayscale charts displaying the variations one-after-another. The participants were asked to follow instructions (i.e., identifying times to plug or unplug a laptop battery) thanks to the charts. In the first two conditions, most of the participants found only the highest peak hour (i.e., global maximum) and failed to find the smaller peak hours (i.e., local maxima); in the third condition (see Figure 2b), they retrieved, however, all the peaks. Whereas forecast data were visualized for the 12 following hours in [29], for the 24 following hours in [53], and for the whole day in [50], in our case, variations are displayed one-after-another in order to benefit of all the variations of a day.



(a) all-at-once (b) one-after-another

Figure 2: Two ways of visualizing variations.

Finding the peak hour of the ongoing variation is necessary for implementing energy shifting. Employees must, however, be notified of an incoming variation without being interrupted or disturbed in their professional activity. CairnFORM has then to be perceivable, but not irritating. Moreover, to create and to encourage new socially-shared energy practices, CairnFORM must be attractive and pleasant in public places.

PREVIOUS WORK

Environment and energy issues became a research topic in Human–Computer Interaction in 1998, by taking the approach of persuasion [8]. The resulting systems have mainly aimed at reducing energy consumption at home, using smartphones [30,41–43,60] and physical representations [1,12,17]. In 2012, the approach framed by persuasion is criticized as it focuses either on changing individuals' behavior [4] and on the current centralized systems of energy production [45]. New directions include focusing on new sociocultural practices [4], designing interactive systems for workplaces and for public or communal spaces, as well as targeting emerging energy systems (e.g., smartgrids, microgeneration, demand response) [45]. This way, some physical interfaces were designed to show the real-time use of energy sources (e.g., central coal power, local solar power, local wind power) [44,46,47], and some graphical interfaces were designed to show energy forecasts in order to shift energy demand at home [3,29,50,53]. Our approach uses actuated physical representations to display renewable energy forecasts in public spaces and at workplaces.

The first tangible user interface using the third actuation loop [19] that maintains the physical state when the data model changes can be attributed to Patten et al. [40] in 2007. This concept is formalized in the terms of Radical Atoms by Ishii et al. [20] in 2012. Close research areas have a similar approach—but with different goals—such as Shape-Changing Interfaces [54] and Data Physicalization [24]. There is some prior work following these approaches, such as Relief [35], inFORM [9], and TRANSFORM [21]. Recent shape-changing interfaces make use of actuators (e.g., mechanical [2], thermal [16], magnetic [34], acoustic [52], pneumatic [64], or biologic [65]) to control the physical properties (e.g., form [18], viscosity [25], volume [27], position [33], texture [35], orientation [57]) of surfaces (e.g., [16]), curves (e.g., [39]) that they use as system input or output. Some shape-changing interfaces that relate to our context use ambient awareness to subtly inform

[2]Pulse: Tangible Line Graph (2012), http://www.dataphys.org/list/pulse-tangible-line-graph/

[3]We use data from http://www.epices-energie.fr/ that provides hourly photovoltaic production forecast for every day.

at offices (e.g., [22,26]). These interfaces exploit ambient awareness—the ability of being aware of the surrounding information [61]—and they are able to move from peripheral attention to central attention of users, and the other way round [59]. Dynamic physical charts [49,55] also relate to our context, but we aim at using one with 360˚-readability.

A typical 360˚-display for public places is iSphere [63]: this flying drone that displays data on its surrounding rotating 88-cm-diameter, spherical screen is designed to inform in stadiums. StaTube [15] is a 360˚-display designed for offices: it displays user states with seven illuminated rings of 6 cm diameter and it is 17 cm high. Vessels of Irelands Past[4] is an example of 360˚-readable chart that is, however, not a dynamic chart. The skeleton of Amphorm [32] is a 33-cm-high tower of five expandable rings that, however, was not designed to display ordinal data and morphs to an 11-point star shape. The closest design that matches our needs are the modular expandable rings proposed by Daniel et al. [7] and Wu [62]. These stackable rings are animated mechanical structures that morph to ring-like shapes. The latter uses six arcs, with gaps between the arcs; the later uses eight overlaying arcs that maintain a continuous circle-like border when expanding. Building upon these works, we developed a prototype of 360˚-readable, physical ring chart.

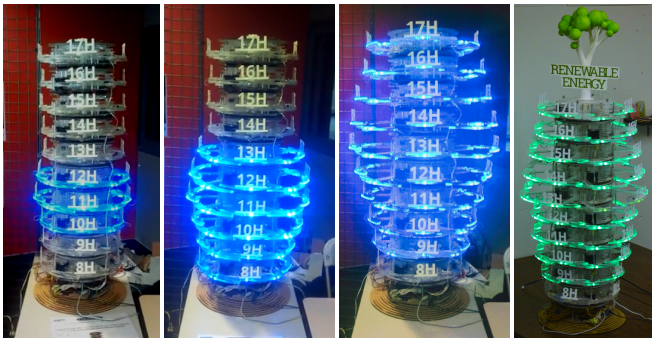
THE CAIRNFORM SYSTEM

In this paper, we focus on the specific context of displaying energy availability in public spaces that opens ways for new socially shared practices in energy Demand-Side Management. In the context of microgeneration, to the best of our knowledge, CairnFORM is the first work that uses a shape-changing ring chart to display ordinal data in public spaces. We designed CairnFORM as an illuminated and dynamic vertical bar chart with cylindrical symmetry that allows 360˚-readability. The major goal is to make renewable energy data available in public spaces in a pleasant and efficient way.

CairnFORM is designed to be pleasant and appealing in order to attract people in public places and to raise discussions about renewable energy. The animation of stacked illuminated rings—in sequence or in parallel—intends to be a playful phenomena and a hedonic experience. Displaying forecasts about renewable energy availability with an appealing interface in public places aims at playing as a socialization element like when people talk about weather forecasts. The aim, in the future, is to lead to new practices such as shifting energy demand in the context of microgeneration. But to do so, CairnFORM has to be usable for peak retrieval tasks.

Beyond playfulness in public places, CairnFORM has to be calm at workplaces, like open-plans and offices. At offices, employees commonly perform tasks on their laptops in the focus of attention (e.g., reading, writing, drawing) using their central vision. To plan a shift, employees must be aware of the next variation to come. However, the employees should be notified of a new incoming variation without disrupting their central attention and without interrupting their main activity. In this context, we want CairnFORM to work as an ambient display that subtly notifies users in their environment. To do so, Gutwin et al. [13] recommend shape-changing stimuli, which are more perceived than light-changing stimuli across the visual field. Consequently, the diameter-change stimulus of CairnFORM, besides being calm, in the workplace context, has to be perceivable enough. CairnFORM aims indeed at assisting employees in new energy consumption practices; it thus has to be efficient to help in saving more energy than it consumes. The main question is the following:

[4]Vessels of Irelands Past #2 (2014), http://tactiledata.net/



(a) V_{3h} (b) V_{6h} (c) V_{9h} (d) V_{9h}

Figure 3: (a)(b)(c) Our CairnFORM prototype, displaying variations of different sizes during a public event. (d) The new design of our CairnFORM prototype.

What is the best motion speed?

To answer this question, we implemented three motion speeds for the rings' diameter change. The best motion speed has to be understood in terms of perceptibility and tranquility. A key problem in designing ambient interfaces is notifying without irritating. We chose the motion speeds so that they are alternatives of different kinds, but equal duration. The first speed is a constant diameter change over time, which can be considered as neutral; the second one is a slow and then accelerating diameter change that follows an exponential curve over time; and the third one is a fast and then slowing down diameter change that follows a logarithmic curve over time. These three kinds of speed are denoted in the following by S_{const}, S_{exp}, and S_{log}, respectively. We applied these three speeds to the two kinds of ring's motion: a full expansion, which increases the diameter from 35 cm to 62 cm, and a full retraction, which decreases the diameter from 62 cm to 35 cm. These two motions were done in six seconds. We denote these two motions in the following by $M_{expansion}$ and $M_{retraction}$, respectively.

Implementation

We designed a prototype of CairnFORM on the basis of modular stackable, expandable, illuminated rings. The design process, the implementation, and the limitations of our ring setup are described in a previous paper [7]. Inspired by a previous solution using six arcs [62], our ring design uses eight overlaying arcs. The ring prototype can expand its diameter from 35 cm to 62 cm. This stackable ring weighs 2.3 kg and takes two workdays to build by one person: 4 hours of laser cutting, 5 hours of 3D printing, 4 hours of

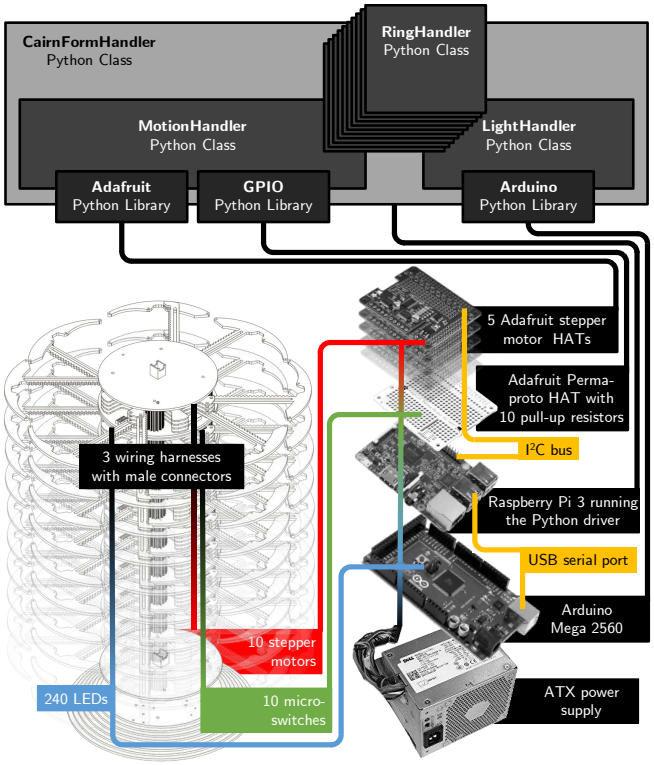


Figure 4: Hardware and software to control CairnFORM.

Element	Min	Max	Parameter
Diameter	35 cm	62 cm	
Color & brightness			24-bit RGB
Motion duration	2 s *(s)* / 3 s *(p)*		
Motion speed			const | exp | log
Motion steps		250 of 1.08 mm	

(s) rings controlled in sequence. (p) rings controlled in parallel.

Table 1: CairnFORM's rings visualization elements.

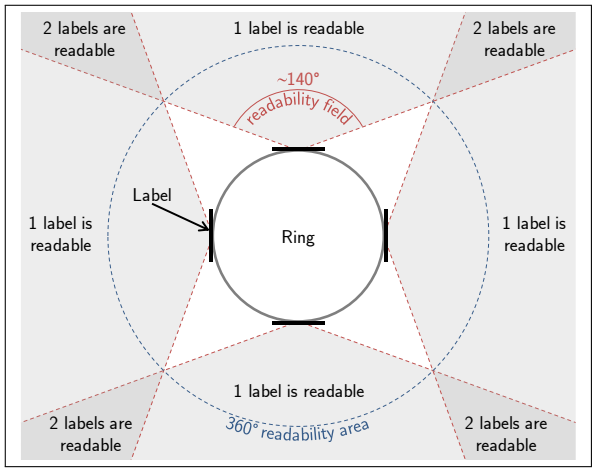


Figure 5: The 360°-readability area of the four labels.

electronics wiring, and 4 hours of hardware assembling. Our modular ring design enables stacking from 1 to approximately 24 rings: adding rings is possible by adding HATs and Arduino cards; but the central column's width limits the wiring harness' growth to approximately 24 rings (The vertical stability of a 24-ring CairnFORM is however not guaranted). A 12-ring CairnFORM is intuitive to present hourly data, but displaying a ten-hours workday—including lunch time—was enough for experimentations. We thus manufactured ten rings and built up a 105-cm-high, 10-ring CairnFORM (see Figure 3), which costs approximately 2,350€ of hardware. The hardware and software to control a 10-ring CairnFORM are illustrated by Figure 4.

CairnFORM's driver can control the rings in sequence or in parallel. The driver is written in Python language (version 2.7), runs on one Raspberry Pi 3, implements four classes, and uses threads and event queues. The source code is available on GitHub[5] under the GPL license. The driver uses a Mosquitto [36] MQTT broker[6] that makes CairnFORM become an IoT device receiving requests from WiFi IP networking.

Our CairnFORM prototype enables visualization elements, such as rings color and brightness, rings diameter, and rings motion at different speed, duration, and steps. Table 1 summarizes the range of these visualization elements. We correlated CairnFORM rings' diameter and brightness to the renewable energy availability: for a power generation capacity ranging from 0 W to *max* W, a fully retracted ring with light off represents a 0 W availability and a fully expanded ring with full blue brightness represents a *max* W availability. We tagged the rings of CairnFORM with 3D-printed labels that mark the ten hours they represent (from 8h00 to 17h59). Four of these labels are glued on each ring (one on each quadrant). These four labels allow a readability area from all around CairnFORM (see Figure 5).

EXPERIMENTATIONS

We conducted two user studies for evaluating CairnFORM. The first study was an into-the-wild user study to see whether the users enjoy the interface and succeed in retrieving information. The second study was a laboratory user study to evaluate and compare the three motion speeds S_{const}, S_{exp}, and S_{log}. The experiments were organized by one person who explained the tasks, demonstrated the use, and collected oral remarks. The participants filled in a written questionnaire in the first study and answered an oral questionnaire in the second user study. These questionnaires were designed to get the answers of the exercises and to get qualitative and subjective feedback about CairnFORM.

First User Study

The first user study was organized as a two-day, into-the-wild usability evaluation during a public event gathering 2,000 visitors (The 24h of Innovation®, December 1-2, 2017, Biarritz, France). This first user study was designed to assess the usability of a 10-ring CairnFORM for information retrieval

[5]Source code: https://github.com/maximedaniel/CairnFORM

[6]MQTT: Message Queuing Telemetry Transport, a messaging protocol where subscribers reveice messages from publishers according to the classes they subscribe.

Variation	Length	Start	Peak	End
V_{3h}	3h	10:00	11:00	12:59
V_{6h}	6h	8:00	11:00	13:59
V_{9h}	9h	9:00	13:00	17:59

Table 2: Design of the three variations.

tasks. 90 visitors were recruited among those who stopped to our booth. These 90 visitors were divided in three equally sized groups that were all with a median of 20-29 years old, but with variable genders and university degrees: (G1) 8 females, 22 males, with a median of 3 years university degree; (G2) 7 females, 23 males, with a median of 2 years university degree; and (G3) 8 females, 22 males, with a median of 2 years university degree.

The exercise required three kinds of low-level information retrieval tasks—range, compare, and order [23]—that we adapted to energy variation. The three information retrieval tasks were the following: (T_{range}) Give the hour range of the renewable energy production; ($T_{compare}$) Indicate the peak hour of the renewable energy production; and (T_{order}) Sort the hours of the variation in ascending order of renewable energy production. One variation of different length was assigned to each group: one of three hours for G1, one of six hours for G2, and one of nine hours for G3. The characteristics of these three variations—denoted in the following by V_{3h}, V_{6h}, and V_{9h}, respectively—are summarized in Table 2; the visualizations of these three variations with CairnFORM are shown on Figure 3. After the exercise, the written questionnaire included the short version of the standardized User Experience Questionnaire (UEQ-S [51]) to measure the subjective impression of users towards the user experience of CairnFORM.

This first experimentation had three main results and two consequences on the design of CairnFORM. The first consequence is to add a 3D-printed, removable model tree on top of CairnFORM, with a label telling what data is displayed; at first sight, one visitor thought the ring chart was a clock and another one thought it was a timer for the public event. The second consequence is to change the rings' color from blue to green; one participant observed that this color goes better with renewable energy. The new design of CairnFORM is shown in Figure 3d. The first result is the easiness we had in recruiting the three groups during the event. The second result is the user experience that was rated both as *good* and *excellent*. The third result is the usability of CairnFORM for T_{range} and $T_{compare}$, which determine variation analyses. Moreover, this latter result provides a use case that extends the results of [23].

Second User Study

The second experiment was organized as a controlled-condition evaluation in our lab. This second user study was designed to qualify the three motion speeds S_{const}, S_{exp}, and S_{log} for animating CairnFORM. We were interested to know which motion speed is the best to inform of a change and to determine which one is the less disturbing and the less annoying, and, before all, which motion speed is the best to unobtrusively notify users in horizontal peripheral vision.

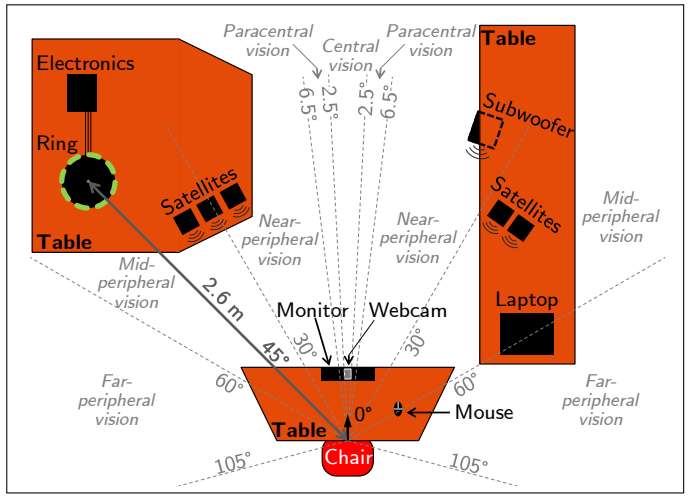


Figure 6: Plan view of the setup of the experiment.

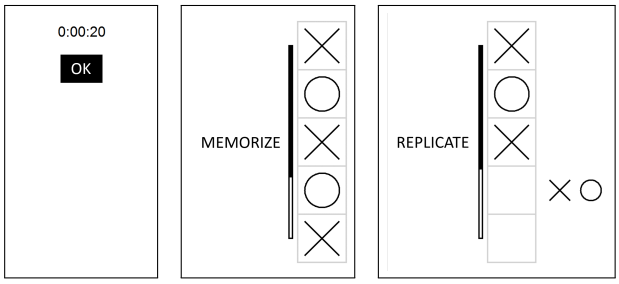
The 30 participants were researchers from our laboratory, staff from the administration department, and students from the campus: 13 of these volunteers were female and 17 were male, aged with a median of 30-34 years old, graduated with a median of 5 years university degree. The apparatus is schematized with a plan view in Figure 6. The participants were sitting on a chair at approximately 50 cm in front of a monitor. A webcam was fixed on top of the monitor. The participants were asked to adjust the height of the seat to align their sight with the webcam. A 1-ring CairnFORM was placed at a distance of approximately 2.6 m away from the head of the participants, in the middle of the mid-peripheral vision[7] (i.e., at an angle of 45° when looking at the center of the monitor). At this distance, the size of the ring covers approximately 7° of the visual field when fully retracted (the region from 41.5° to 48.5°) and approximately 14° when fully expanded (the region from 38° to 52°): the ring stays in the mid-peripheral vision.

We had to reduce the noise of our ring prototype. We placed 5 cm of foam under the ring to limit propagation and amplification of vibrations by the table—the noise decreased from 60 dB to 50 dB when measured[8] at a distance of 1 m. The remaining noise was masked by asking the participants to wear 30-dB-SNR-attenuation ear defenders and by playing white noise with a 5.1 surround sound system speaker placed in front of the participants[9] (see Figure 6). This setup allowed the participants to perceive the ring's motion only thanks to the peripheral vision. The participants were also told to focus on the screen and not to look at the ring during the two following exercises. These two exercises aim at catching the ring's motion with the peripheral vision, but with different attention levels: one is with the focus of attention (i.e., focusing attention on the detection task) and the other

[7]The mid-peripheral vision—covering the region from 30° to 60°—defines the limit of the upwards peripheral vision [13].

[8]Repeated measures with three apps on a smartphone and a tablet.

[9]The white noise was played for short durations during the trials; it was turned off when giving the instructions and when filling in the questionnaires.



(a) $T_{detection}$ (b) $T_{perception}$ (c) $T_{perception}$

Figure 7: Screens of the two tasks.

is with the periphery of attention (i.e., ambient awareness; because another task gets the focus of attention).

The first exercise allows training and learning perception with peripheral vision. This exercise consists in detecting six ring's motions (three expansions and three retractions) while focusing on a 25-second timer that is running at the center of the monitor's screen. When detecting a ring's motion—with the peripheral vision—the user must click a button beneath the timer with the mouse pointer (see Figure 7a). Motions are randomly triggered by the computer between 5 seconds and 15 seconds. We denote this task in the following by $T_{detection}$.

The second exercise tests ambient awareness. This exercise is based on a series of seven short-term memory tasks. For each of the seven trials, the user must memorize during ten seconds a sequence of five symbols (crosses and circles, see Figure 7b). Then, the user must replicate the sequence one symbol at a time: every two seconds the user must recall the next symbol of the sequence by clicking on the symbols displayed at the right of the screen (see Figure 7c). When replicating, a ring's motion can occur or not: three expansions and three retractions occur, but one trial is motionless. After each trial, the users answer whether a ring's motion occured and whether it was an expansion or a retraction or whether they don't known. We denote this task in the following by $T_{perception}$.

This experiment follows a within-subject design: the participants went through the two exercices with the three motion speeds. The order of the speeds was counterbalanced using a Latin square and the same order was kept for the exercises of a user. These exercises, however, were tiring; including demonstrations and training trials before each exercise, and written questionnaires afterwards with each speed condition, the whole session lasted approximately 45 minutes per user. Moreover, focusing attention and replicating sequences is a hard work. Before starting the next phase with the exercise 2, sweets and orange juice were offered to the participants in order to maintain well-being and performance.

The data were available for 1,080 ring motions. We used the facial expression analysis software FaceReader 4 on the video recordings of the webcam to detect if participants gazed at the ring. We post-processed manually the resulting log files to validate or unvalidate the gaze retained by FaceReader. We then erased the reaction times that were recorded when the users gazed at the ring or when the ring was motionless. We approximated the perception time from the reaction times by subtracting 200 ms. This duration is the minimum time for the brain to perceive, process, and response to a visual stimulus[10].

	Success rates			**UEQ-S qualities**	
	T_{range}	$T_{compare}$	T_{order}	*Hedonic*	*Pragmatic*
G1 – V_{3h}	100%	93.3%	80.0%	2.25 pts	1.75 pts
G2 – V_{6h}	93.3%	93.3%	63.3%	2.25 pts	1.75 pts
G3 – V_{9h}	86.6%	90.0%	13.3%	2.25 pts	1.50 pts
Average	93.3%	92.2%	52.2%	2.25 pts	1.67 pts
	***p*-values**			***p*-values**	
	(1)	(1)	(1)	(2)	(2)
$V_{3h}/V_{6h}/V_{9h}$	.12	.85	**.001**	.17	.26
V_{3h}/V_{6h}	.49	1	.25	.84	.67
V_{3h}/V_{9h}	.11	.64	**.001**	.81	.23
V_{6h}/V_{9h}	.67	.64	**.001**	.94	.39

The qualities range from -3 to 3 pts. P-values under 0.05 are in bold print. (1)Pearson's chi-squared test when 3 groups; Fisher's exact test when 2 groups. (2)Kruskal–Wallis's rank sum test when 3 groups; Cochran–Artimage's trend test when 2 groups.

Table 3: Success rates of the three information retrieval tasks and UEQ-S scorings for the three groups of visitors.

As we will see below in the results section, this second experimentation provides a use case arguing that a non-constant speed is better than a constant speed.

RESULTS OF THE USER STUDIES

This section presents and discusses the results that both benefit to the energy Demand-Side Management domain and to the scope of Shape-Changing Interfaces design. Ratings are ranked on a 7-point scale for UEQ-S, from -3 to 3 pts, and on a 5-point scale for other questionnaires, from -2 to 2 pts.

Benefits for Demand-Side Management

A Usable Display for Variation Analyses

The two tasks T_{range} and $T_{compare}$ are useful for variation analysis for shifting energy: identifying the variation's range and retrieving the peak hour. The average success rate for these tasks was over 90%. Moreover, the variation's duration had no effect on the success rates of T_{range} and $T_{compare}$ ($p = .12$ and $p = .85$, respectively, with Pearson's chi-squared test). These results makes CairnFORM usable for new energy practices that require variation analyses, such as shifting energy. Table 3 shows the success rates of the three groups for these two tasks.

Five participants, however, pointed out the difficulty to differentiate the rings' diameter. The experiment was done with a 30-point data scale; the radius granularity was 9 mm. Decreasing the data scale is unnecessary regarding the successful variations analyses, for T_{range} and $T_{compare}$, from an observation distance of approximately 1 m. Moreover, some participants did a backward step to have a larger view of CairnFORM. The granularity is linked to the observation distance; its value should be determined according to the context of use. The observation distance may be longer in public places than in open-plans.

[10] 150 ms of visual processing [56] and 50 ms of muscle response for healthy patients [48].

A Useful Display for Public Spaces

The into-the-wild experiment revealed the attractivity of CairnFORM in public places. CairnFORM was installed in the access hall, mid-way to the central event. Hundreds of visitors stopped to see CairnFORM and talked about it. Recruiting visitors to answer questions was easy. We succeeded in recruiting 90 visitors over 16 hours, which is about 10 minutes per person comprising about 5 minutes of explanations and 5 minutes of questioning. Over a novelty effect, CairnFORM can play socialization role in public places as being rated hedonic and pragmatic.

The UEQ-S scores reveal that CairnFORM has *good* hedonic quality and *excellent* pragmatic quality. The average scores, given by the three groups, were 2.25 pts and 1.67 pts, respectively. Table 3 shows the UEQ-S scores for each group. This user experience is supported by written and verbal remarks, about hedonic aspects: *"Pleasing."*, *"Esthetic and avant-gardist."*, *"Exquisite."*; and pragmatic aspects: *"[CairnFORM] being readable from 360° is useful especially for persons with reduced mobility."*

Installing CairnFORM at workplaces, such as offices or open-plans, requires not disturbing the workers, but being perceivable. Memorizing and replicating the sequences was done successfully: the participants correctly replicated 97.78% of the 540 sequences (6 errors with S_{const}, 4 errors with S_{exp}, and 2 errors with S_{log}, on 180 trials each) and 99.99% of the symbols (2,680 of the 2,700 symbols to replicate). Yet, memorizing five symbols in ten seconds and replicating it every two seconds requires concentration. This convinces us that the ring's motion seems appropriate to preserve the focus of attention on a work task at workplaces.

Benefits for General Shape-Changing Interfaces Design

Dynamic Physical Charts

We extend to physical ring charts the results of Jansen et al. [23] who studied low-level retrieval tasks with physical bar charts. They show that users do a compare task slower than a range task, but faster than an order task. The success rates of our experiments reveal that users do a compare task (92.2%) less well than a range task (93.3%), but better than an order task (52.2%). Thus, according both to completion time and success rate, physical bar charts and physical ring charts (i.e., physical vertical bar charts with cylindrical symmetry) seem better suited to range tasks and compare tasks, rather than order tasks.

The low success rates seem inherent to the order task. The success rate of T_{order} indeed decreases as the length of the variation's range increases. This effect of the variation's length is significant ($p = .001$, Pearson's chi-squared test). The difference between the success rate of V_{9h} (13.3%) and the succees rates of V_{3h} (80.0%) and V_{6h} (63.3%) is significant (equal $p = .001$ and $p = .001$, with Fisher's exact test). We hypothesize that this is caused by our limited capacity for processing information [38]: comparing each value on the two gradients before and after the peak requires doing many visual comparisons while remembering the previous values already compared. This becomes rapidly very difficult. Further investigations should confirm these observations.

Visualization and Stimulus Elements

Nine participants of the first study reported their difficulty to differentiate the rings' brightness. The problem is that when one arc is close to another, the light shines and reflects from one arc to another. This results in an overall over-illumination. As suggested by one participant, color-change could be better than brightness-change. However, as the diameter already represents the variation, we prefer keeping color-change to represent further information.

The measures were similar for the two kinds of motion (expansion and retraction). The detection times and the distance covered by the ring when detected were similar for $M_{expansion}$ and $M_{retraction}$ in the three speed conditions. Moreover, it was also possible for the participants to recognize the kind of motion with peripheral vision and the periphery of attention: they succeeded in recognizing 87.1% of $M_{expansion}$ and $M_{retraction}$. These results make the kind of motion a possible visualization element.

The real detection stimulus is diameter change, not the acceleration. The motion speed detected with the smaller diameter change was S_{const} (8.92 cm). The motions with speeds S_{log} and S_{exp} were significantly perceived at the same diameter change (10.58 cm and 10.57 cm, respectively, $p =$ .01 with Student's t-test). This observation suggests that, independently from the acceleration, a diameter change is detected after it has travelled a critical distance in the visual field [11,28] (10.58 cm at 2.6 m represents 2.74° in the visual field and 1.37° of change on each side of the ring). As we will see below, however, the motion speed has an effect on success rates and tranquility.

Motion Speed

On the one hand, the participants rated not being distracted by the ring (1.2 pts in average for the three speeds) when focusing on the main task of replicating the sequences. Also, the kind of speed had no effect on distraction ($p = 0.73$, Kruskal–Wallis's rank sum test). These observations show that quiet and slow motion—all rings' motions were done in 6 s—help in keeping focused on the main task.

On the other hand, the motion speeds had an effect on the easiness, in the two tasks $T_{detection}$ and $T_{perception}$ ($p = 0.01$ and $p = 0.04$, respectively, with Kruskal–Wallis's rank sum test). First, for the two tasks, S_{const} was rated as less easy than the two other speeds. Second, whereas S_{log} was rated the easiest (1 pt) for $T_{detection}$ with significant difference with S_{const} (-1 pt) and S_{exp}(-0.75 pts) ($p = .001$ and $p = .02$, respectively, with Cochran–Artimage's trend test), S_{exp} was rated the easiest (1 pt) for $T_{perception}$, but without significance.

Few motions were unseen during $T_{detection}$: the average detection rate is 94.33% for the three speeds. The motion speed had no effect on these success rates of the task ($p = .73$, Pearson's chi-squared test). The motion speed had however an effect on the success rates of $T_{perception}$ ($p = .004$, Pearson's chi-squared test). The perception rate of 72.2% for S_{exp} is significantly higher than 60.5% for S_{const} and 66.5% for S_{log} ($p = .002$ and $p = .03$, respectively, with Fisher's exact test). These observations validate that the non-constant speed of S_{exp}

	$T_{detection}$					$T_{perception}$			
	Detection rate	*Detection time*	*Distance covered when detected*	*Easy to detect*	*Calm motion*	*Perception rate*	*Easy to perceive*	*Calm motion*	*Not distracting*
S_{const}	93%	1.99±1.37 s	**8.92±6.40 cm**	-1 pt	**1 pt**	60.5%	-0.25 pts	**1 pt**	**1.5 pts**
S_{exp}	**95%**	3.38±1.20 s	10.58±6.47 cm	-0.75 pts	**1 pt**	**72.2%**	**1 pt**	**1 pt**	1 pt
S_{log}	**95%**	**1.18±0.95 s**	10.57±5.54 cm	**1 pt**	0 pts	66.5%	0 pts	0.5 pts	1 pt
	***p*-values**					***p*-values**			
	(1)	(2)	(2)	(3)	(3)	(1)	(3)	(3)	(3)
$S_{const}/S_{exp}/S_{log}$	.73	**.001**	**.004**	**.01**	**.03**	**.004**	**.04**	.54	.73
S_{const}/S_{exp}	.63	**.001**	**.002**	.80	.46	**.002**	**.04**	1	.66
S_{const}/S_{log}	.63	**.001**	.47	**.001**	**.02**	.26	.78	.35	.48
S_{exp}/S_{log}	1	**.001**	**.01**	**.02**	.09	**.03**	.08	.31	.75

The scores' range is from -3 to 3 pts. Best scores and p-values under 0.05 are in bold print. (1)Pearson's chi-squared test when 3 groups; Fisher's exact test when 2 groups. (2)ANOVA test when 3 groups; Student's t-test when 2 groups. (3)Kruskal–Wallis's rank sum test when 3 groups; Cochran–Artimage's trend test when 2 groups.

Table 4: Success rates, measures, and scorings for the two exercises with the three speeds.

outperforms the constant speed of S_{const}. Beyond efficiency, the remaining question is about tranquility.

The participants rated whether the ring's motion was calm. Whereas the kind of speed had an effect on these ratings in $T_{detection}$, it had no effect in $T_{perception}$ ($p = .03$ and $p = .54$, respectively, with Kruskal–Wallis's rank sum test). For the two tasks $T_{detection}$ and $T_{perception}$, the speed S_{exp} was however rated as calm as S_{const} with 1 pt for both, and S_{log} was rated as the less calm with 0.25 pts in average. Finally, S_{exp} is rated as calm as S_{const} and is better perceived than S_{log}: all these observations argue for S_{exp} being the more appropriate ambient awareness motion. Table 4 shows the measures and scorings of the two tasks $T_{detection}$ and $T_{perception}$ for each speed.

GENERAL DISCUSSION

The first experiment explored low-level information retrieval tasks with a 10-ring CairnFORM. The success rates of over 90% show that CairnFORM is usable for the two tasks T_{range} and $T_{compare}$. These results on success rates extend the results of Jansen et al. [23] on completion times to physical ring charts. Moreover, our results show that the success rates of T_{order} decrease significantly with increasing variation duration, whereas the success rates of T_{range} and $T_{compare}$ remain high. Our physical ring chart, however, combines color and diameter as visualization elements; this leaves room for other experiments studying diameter change only.

The second experiment explored ambient shape-changing notification. We hypothesize that continous speed changes affect perception rates in peripheral vision. Kobayashi and Yamada [31], and Jones et al. [26] evaluated slow and quiet motion using shape-changing interfaces: but the later tested motion out of the view field, and the latter tested constant speed only. Traschütz et al. [58] study the detection instantaneous speed change in peripheral vision. They show that speed changes above 50% are more reliably detected than intermediate speed changes of 10–25% that elicit low detection rates, what explains why constant speed was less detected and less perceived than non-constant speeds in our case. Traschütz et al. [58] also show that acceleration and deceleration detection rates differ; this can explain why the perception rates differ from an exponential speed and from a logarithmic speed.

The present studies reveal the attractivity of CairnFORM in public places, show its usability for variation analyses, and find the best motion speed to notifiy changes in peripheral vision. These results convinced us to evaluate the daily use of CairnFORM displaying renewable energy availability for shifting energy demand. A two-month user study is currently ongoing at a workplace.

CairnFORM opens new perspectives to display data in social spaces where people come from and go to different directions; there is great potential for useful applications. For example, physical ring charts could display tides in a harbor, traffic flow on roundabouts, shop affluence in the entrance hall of a mall, ultraviolet index at a beach, or air quality in a public park.

CONCLUSION

We presented CairnFORM, a new 360°-readable, dynamic physical ring chart that displays forecasts of renewable energy availability. CairnFORM aims at creating and encouraging new socially-shared energy shifting practices in collective and public spaces, such as public places and workplaces. We conducted two user studies on our use case of CairnFORM, which had two main results. First, the success rates of the first user study show that, with our physical chart, users do a compare task (92.2%) less well than a range task (93.3%), but better than an order task (52.2%). Second, the second user study shows that exponential motion speed, besides being rated as calm as a constant speed, is 19.3% better perceived than a constant speed with the peripheral vision in ambient awareness conditions. The first result completes the previous results on physical bar charts completion times. The second result provides a use case arguing for an exponential speed to subtly notifying users with peripheral vision. Moreover, the user studies reveal that CairnFORM is usable for peaks retrieval tasks that are necessary for energy shifting practices, and they show the best motion speed to implement CairnFORM at a workplace. As future work, promising research investigates short-term and long-term user studies of such physical charts in order to put socially-shared energy shifting practices into effect.

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