Advanced Interaction and VR/AR

Can a Green Thumb Make a Difference?

Using a nature metaphor to communicate the sensor information of a coffee machine.

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This article describes a novel visual metaphor to communicate the sensor information of a connected device. The Internet of Things (IoT) aims to extend sensing and computing capabilities to every device. A byproduct of this is that even domestic machines become increasingly complex and more difficult to understand and maintain.

We present a prototype of a coffee machine outfitted with sensors. The machine streams the sensor data, which are picked up by an augmented-reality (AR) application conceived as a metaphor from nature. The metaphor, BioAR, represents the status derived from the coffee machine sensors in the form of a three-dimensional (3-D) virtual tree. The tree is meant to serve as a living proxy of the machine it represents. The metaphor, shown by using either AR or a simple holographic display, reacts to user manipulation of the device.

A first user study validated that the representation was correctly understood and that it inspired emotional connection with the machine. A second study confirmed that the metaphor scaled to a large number of such devices.

THE QUEST FOR CALM TECHNOLOGY

The IoT concept presents a great potential to impact many aspects of human life. In the IoT paradigm, connected devices possess embedded sensors and can communicate

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real-time sensor information. The complexity of connected devices varies from the extremely intricate industrial machines found on factory floors to the mundane appliances in our homes. Both professional and personal environments are being enriched with connected devices, which support or perform many of our daily tasks—although maintenance and reconfiguration work still demand human expertise and intervention. The abundance of smartphones and the cloud infrastructure have laid much of the way for the IoT [26].

Weiser's vision for so-called calm technology [14], [15] is now a possibility that is within reach. This notion puts the focus on calming, suggesting that humans need to be informed, but not overloaded with information. Therefore, technology should, as much as possible, become invisible, calling our attention only when necessary. The goal of our research was to communicate information about complex, real-time processes in an engaging, interactive, and open manner. We felt that the representation should be esthetically pleasing and increase overall well-being.

The nature metaphor BioAR was inspired by the Biophilia hypothesis, which postulates that people tend to be drawn to life and lifelike processes [1]. Moreover, being close to nature and representations thereof has beneficial effects on people's emotional, cognitive, and physical well-being. Even contact with artificial plants, natural-light-like illumination, and nature photography contributes to a healthier environment [4].

We based our work on the premise that if machines are perceived to be more like living beings, users will take better care of them, which ideally would translate into better maintenance. Thus, we intended to endow a machine with a representation that would make it seem alive. We chose AR (BioAR) as a means of extending a device through a nature visualization. AR comprises technologies aimed at adding computer-generated 3-D graphics to the real world.

RELATED WORK

BIOPHILIA AND ANTHROPOMORPHISM

According to Webster's dictionary, anthropomorphism is the attribution of human characteristics or behaviors to objects or animals. Anthropomorphism is surprisingly common. Take, for example, the children's stories in which animals, machines, and cars can talk and act like humans. People tend to anthropomorphize when 1) anthropocentric knowledge is accessible and applicable, 2) motivated to be active social agents, and 3) missing a sense of social connection to other humans [6]. The anthropomorphic form, often incorporated in product design in an abstract way (e.g., the human-like shape of a bottle, or humanoid robots), is used to attract attention and establish emotional connection [5].

Humans are hardwired to be social and experience emotions such as empathy and compassion toward other humans and living beings in general. Research has been conducted to understand how people interact with anthropomorphic machines (e.g., robots). The perception of a machine's intelligence and consciousness, combined with anthropomorphic factors (appearance, gestures, and emotions), change the dynamics of human–machine interactions. Machines are often perceived as social actors [8], meaning that social rules and dynamics can be used to design systems that change users' behavior [9]. For example, the rule of reciprocity ("If you help me, I feel I should help you") also applies in human–machine relations [11].

Bartneck et al. designed a study where they asked two groups of users to play a game collaboratively with a talking cat-robot [7]. In one of the groups, the robot was quite helpful, while in the other, not so much. Afterward, the participants were instructed to turn off the robot. Their perception of the robot's intelligence and agreeability had a strong effect on their hesitation to switch it off. The group with the most helpful robot hesitated almost three times as long to shut it down; essentially, killing the machine was difficult because an emotional connection had been created with it [7].

People tend to establish a long-term, social–emotional relationship with their computers, cars, and phones, to name a few machines in our lives. While humans may treat devices as people, even if they do not perceive that they do and deny it [11], machines are not capable of recognizing the emotions of their users. Nonetheless, we can improve human–machine interaction by creating augmented machines that recognize human emotions and adapt their own behavior accordingly, i.e., so-called affective computing [12].

AR AND HOLOGRAPHY

AR combines real things with virtual objects, enhancing both perception and interaction with the real world. AR aims to simplify people's lives by making virtual information available when needed. Potentially, AR can include all of the human senses (i.e., vision, smell, hearing, touch, and taste) to create a more holistic interaction [17].

> If the adoption curve for VR and AR technologies is similar to smartphones, we may be using these technologies daily in the next seven to ten years.

Virtual-reality (VR) and AR technology hold the potential to replace traditional displays in many contexts. As soon as VR and AR devices are mature enough to provide a flawless and enjoyable experience at a reasonable price, they will become a profoundly disruptive technology. If the adoption curve for VR and AR technologies is similar to smartphones, we may be using these technologies daily in the next seven to ten years [24]. It therefore becomes crucial to consider how these technologies can help turn the often-challenging complexity of modern machinery into an appealing experience. Applications to visualize complex machinery in AR have taken various approaches, and different displays are used to realize them.

The majority of AR applications (e.g., marketing, commercial, professional, educational, and entertainment) focus on visual stimuli. These applications typically use AR displays, which can be classified as head-mounted (e.g., glasses and helmets), handheld (e.g., smartphones and tablets), and spatial (e.g., video projectors and holograms) displays, each type offering advantages for specific use cases. Handheld displays are now mainstream, a ubiquitous AR display owing to the broad adoption of smartphones. Head-mounted displays have supporters in professional areas that require hands-free interaction with real objects. Wearable devices like smart glasses have the power to bring AR into everyday life [28]. We implemented our prototype in a minimalistic version of the virtual showcase [31].

Spatial AR was effectively used for IoT-like applications, as in an augmented kitchen where appliances communicate to people (e.g., listing the contents of the refrigerator) and support users without interfering with the task itself (e.g., projecting a recipe or pointing to a cabinet) [18], [19]. Notably, research on AR visualization has concentrated on metaphors to present comprehensive instructions using the technique [19]. Prominent metaphors have adopted known artistic methods of visual communication and concentrated on generating multiperspective explosion diagrams [19], dynamic label placement techniques [19], and ghosted views in AR [19].

With respect to information from sensors, conventional visualizations have been used in AR to visualize multivariate, real-time sensory data [2]. An important issue for comprehensive, coherent AR methods is the need to be adaptive to changes in viewpoint, illumination, and colors [19]. Close to our concept, Pokric et al. deployed an AR application on handheld devices (Android and iOS), featuring a virtual 3-D avatar on a marker. The measurements obtained from an IoT environmental sensor affect the avatar aspect [30].

Despite the fact that AR poses major perceptual challenges, data representations in AR are rarely perceptually validated, with the exception of the detailed studies on legibility by Gabbard et al. [10]. Real-world things may interfere with the correct decoding of AR visualizations and have negative effects on scene coherence [16]. Therefore, AR interfaces should take into consideration not only what information to show users, but also when and how to present it.

A CONNECTED COFFEE MACHINE

A coffee machine is a domestic device that people use in their daily lives. Although its operation is simple, several conditions must be observed both for a quality cup of coffee and the health of the device itself. People understand the operative factors of a coffee machine but often miss the maintenance aspects that can harm both the machine's health and the coffee's quality. Several coffee machine models belong to the new generation of IoT devices, but there are no open-source application programming interfaces to access their sensor data.

Therefore, we constructed a customized IoT coffee machine that matched our requirements, following an approach of adapting nonconnected devices to create IoT gadgets out of ordinary consumer goods [27]. Both hardware and software solutions are available on the market for such do-it-yourself projects [25].

HARDWARE

We extended a basic coffee machine with sensors of three types: an Ultra-Sonic Sensor HC-SR04 in the water tank to measure the water level, two force-sensitive resistors (one at the top of the coffee capsule drawer to detect the presence or absence of the capsule and the other over the on-off button to record the button press), and a Temperature Sensor LM35 inside the machine to measure the water temperature.

A microcontroller collects the data from the sensors and uses an Ethernet module to transfer them to an MQTT server (lightweight message protocol). For convenience, we built a hardware interface to set the desired status of the machine. This feature allowed us to manipulate the sensor data (e.g., to increase the temperature) and simulate critical errors merely by pressing a button.

Several operational aspects of this basic prototype are transferrable to other machines in more complex processes: raw materials are used to produce a product (e.g., coffee capsules to produce coffee), fluids must be maintained within acceptable ranges (e.g., the amount of water for the coffee), waste materials have to be removed (e.g., used coffee capsules), the temperature of the machine must fluctuate within an acceptable range, and maintenance is required to ensure the quality of the product and the health of the device (e.g., decalcification).

IMMERSIVE DISPLAY

Devices hosting the BioAR application pick up and display the sensor data. We built the application in a cross-platform game engine. It runs an MQTT client that subscribes to sensor data streams from the outfitted coffee machine and presents the corresponding visual representation.

The interaction between man and machine is mediated by the nature metaphor. We deployed two applications: an AR application running on a smartphone and a holographic application working on a simple display. As the user operates the machine and the sensors pick up different conditions, the AR display reflects the status changes.

The AR application uses an AR SDK module to register the visualization with a marker (see Figure 1). Other researchers have previously used AR to display multivariate, real-time sensory data using conventional visualizations [2]. BioAR uses a marker next to the machine; it is detected and tracked using the AR SDK internally, and a 3-D tree representing the machine status is displayed. The AR application presents a plausible solution to visualize the metaphor, bringing into reality a sensing representation of the machine. The disadvantage of AR is that a device is required to actually mediate the view, and putting the apparatus down disrupts the metaphor.

We constructed the holographic application to counter this disadvantage. Figure 2 depicts the prototype structure. It consists of a flat-panel monitor connected to a personal computer and a flexiglass pyramid that reflects the four-side rendering of the 3-D object, creating the illusion that the projected object is floating in midair. The desktop application creates a multiple-surface projection of a 3-D tree model, using four cameras with a 90° interval to capture four views of the model. An arbitrary number of users can experience the holographic application, but it requires a larger infrastructure sitting next to the machine. An advantage is that the experience is available even without pulling out one's phone.

BioAR: A NATURE-INSPIRED VISUAL ENCODING

We used a tool kit to create several 3-D models of the trees, which represent the different states of the coffee machine. These 3-D models are the basis of the BioAR tree metaphor.

TREE METAPHOR

In our nature-inspired metaphor, trees represent single machines. The machines' sensory data are encoded into the various visual features of the BioAR tree metaphor. The operator is expected to infer the general state of a machine by assessing the tree appearance. To get more details, a user can visually examine a specific property of the tree.

As the user operates the machine and the sensors pick up different conditions, the AR display reflects the status changes.

VISUAL ENCODING

The tree metaphor we designed to encode the machine status allows for three main elements: water level, temperature, and elapsed time before maintenance.

1) The water level of the tank is represented by the thickness of the tree's greenery. Figure 3 depicts the three considered levels: low-density foliage (the tank is less than one-third full), medium-density leaves (the water level is greater than one-third but less than two-thirds of the way up), and dense foliage (the tank is more than two-thirds full).

FIGURE 1. The BioAR, seen through a handheld AR device (a 5.5-in mobile phone). The BioAR nature metaphor represents the sensor data that define the status of the coffee machine in the features of a virtual tree.

(a) (b) (c)

FIGURE 2. A BioAR holographic display. (a) The sensor-outfitted coffee machine streams sensor data that are encoded in a holographic tree. (b) The structure of the holographic display consisting of a 17-in flat monitor and a flexiglass pyramid. (c) A detail of the four-side rendering of the 3-D object.

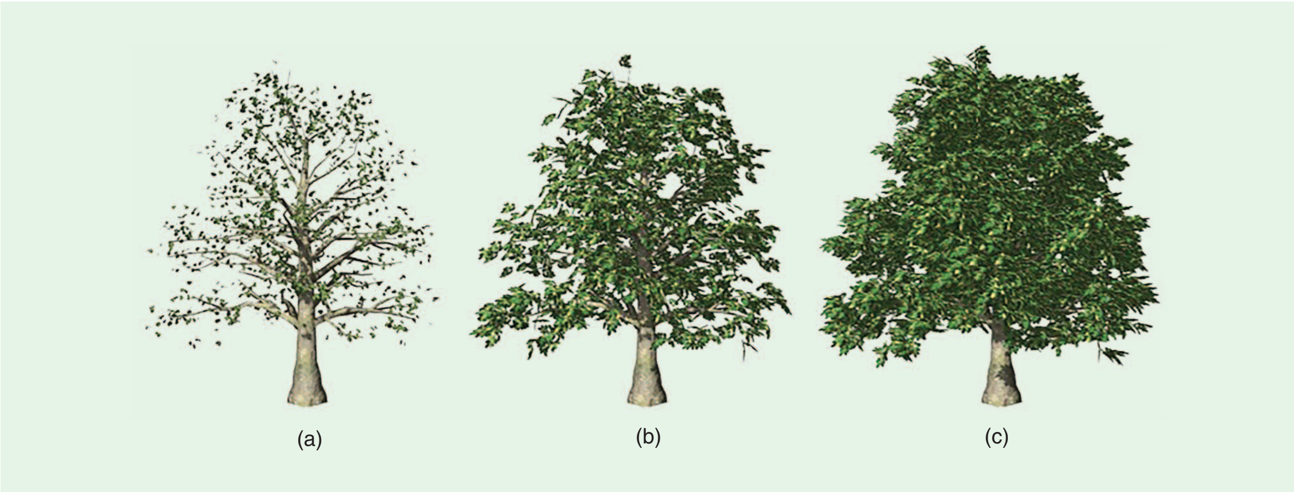

FIGURE 3. The coffee machine's water tank level is encoded in the foliage density. Three levels are considered. (a) Low-density foliage is displayed if the tank is less than one-third full. (b) Medium-density foliage represents a water level that lies between one-third and two-thirds full. (c) Dense foliage indicates that the tank is more than two-thirds full.

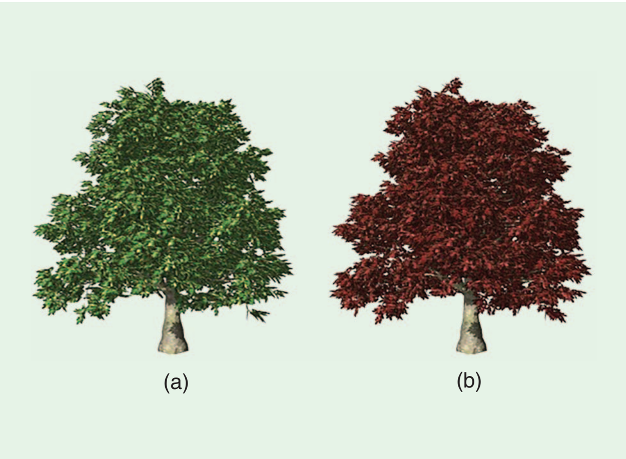

FIGURE 4. The foliage color encodes the machine temperature. Two states are considered. (a) The tree with green leaves represents the temperature being within the operational range. (b) The tree with red leaves indicates that the temperature is not in the operational range.

2) Temperature is represented by the leaf color (Figure 4). We considered two states: green leaves if the temperature is within the operational range (20–60 °C), and red leaves if it is above or below that.
3) The number of cups of coffee that have been made is represented by the presence or absence of magnolia flowers, as shown in Figure 5. The number of coffees brewed indicates when the machine requires upkeep (its maintenance status). The absence of flowers means that the machine is running under duress because a cleaning is long overdue. The presence of flowers indicates that the machine is operational. The size of the flowers denotes when the next maintenance episode is required. We encoded three possible states: small flowers indicate that a cleaning will be required soon, medium-size flowers point to an intermediate state, and large flowers signify that the machine will not require maintenance for a while, possibly because upkeep has just been performed.

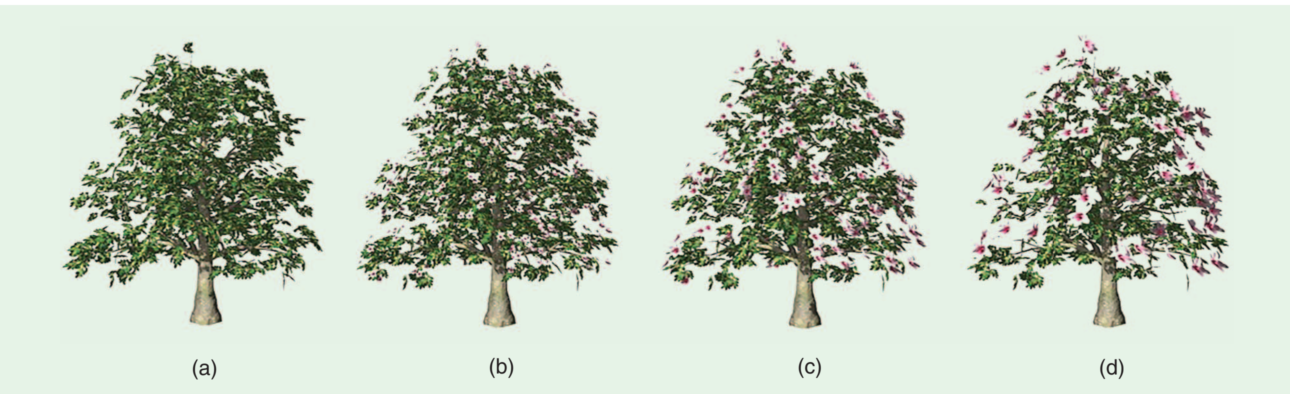

FIGURE 5. The flower size encodes the time to the next maintenance episode. Four states were considered. (a) The tree has no flowers if the machine's maintenance is long overdue. (b) and (c) Intermediate states of the coffee machine are represented by intermediate flower sizes. (d) The tree has large flowers if the machine was just serviced.

Additionally, a coffee capsule can be present or absent in the container. Before brewing the coffee, the operator should insert the capsule. Once the capsule is inside the machine, the tree is highlighted, simulating via animation the sunlight washing over the leaves, as depicted in Figure 6. Finally, if a critical error occurs, the machine is represented by a dead tree, as illustrated in Figure 7, indicating that no coffee can be brewed and that the machine requires technical service.

EXPERIMENT 1: UNDERSTANDABILITY AND AFFECT

This experiment aimed to validate if participants could read the sensed status from the nature-inspired encoding and to assess if BioAR is appealing. We measured errors in interpreting the BioAR tree metaphor encoding as well as engagement and overall subjective satisfaction with the machine.

APPARATUS

We used the BioAR prototype with the sensor-equipped coffee machine connected to the holographic tree display. The experimenter could set the machine to any desired state using the available hardware interface to control the sensor data. We made ingredients and equipment ready for participants to brew their own coffee, including capsules with different types of coffee, mugs and spoons, and sugar and cream. A pot of water was available for participants to refill the machine.

PROCEDURE

We organized the study as a showcase, with a cognitive walkthrough of the possible states of the machine. We invited participants in groups of three, with each group being introduced to the machine and the concept as part of the showcase. The subjects—eight males and four females, four aged 20–29, seven 30–39, and one 40–49—received an illustrated description of the encoding. After a brief introduction period, we asked the participants to brew themselves coffee, giving them the chance to interact with the machine (Figure 8).

We randomly distributed the possible machine states and their representations into 14 experimental conditions, resulting in 168 answers for each of the five variables. The participants took turns approaching the machine, which the experimenter set to the appropriate state; we then asked them to observe the tree hologram and mark the machine status on a sheet of paper. Thereafter, the subjects filled out a questionnaire about their experience.

RESULTS

The participants gave fully correct answers for all of the five variables in each of the 14 experimental conditions in 120 out of 168 cases. The median of these fully correct answers by participant was 11 (ranging between six and 14). Identifying the maintenance status, determined by the number of coffees made and shown by the presence and size of flowers, occasioned the largest number of incorrect answers (the total score for this variable was 130 out of 168; median = 12), followed by categorizing the water level (total score of 155 out of 168;

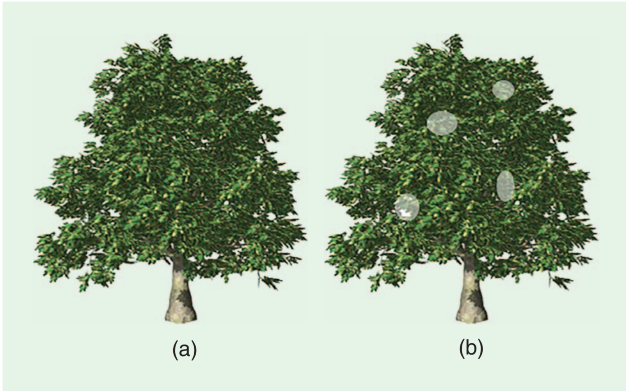

FIGURE 6. The presence or absence of sun highlights encodes whether the capsule is inserted or not. (a) A tree with no highlighting, if the capsule is absent. (b) A tree with sun highlighting, if the capsule is present.

FIGURE 7. An image of a dead tree illustrates that there is a critical error in the machine.

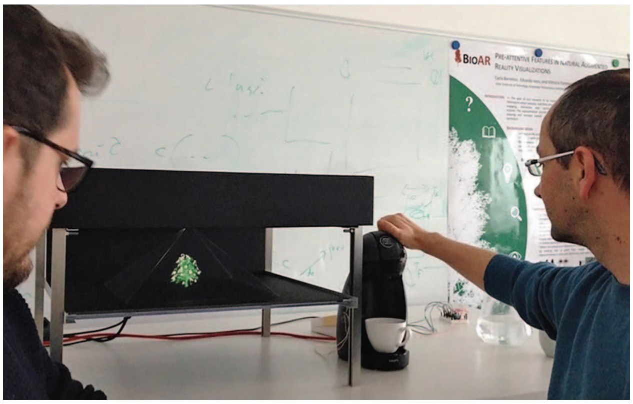

FIGURE 8. Two participants in the study on understandability and affect interact with the coffee machine and observe the consequences of their actions in the AR tree in real time.

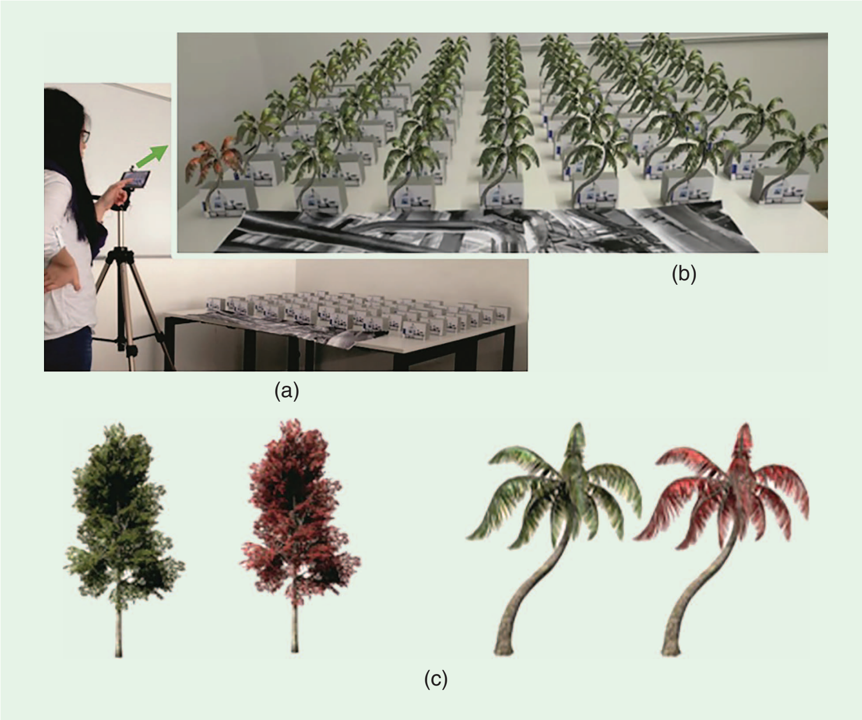

FIGURE 9. A study on scalable perception. (a) A participant observes a forest of trees, each representing a machine. (b) A close-up of the trees. (c) The four possible aspects of a tree for this study.

median = 14), which was displayed using the amount of foliage. In contrast, participants easily identified the presence or absence of the capsule (sun highlighting), the temperature (foliage color), and the critical error (dead tree) (165, 168, and 167 out of 168, respectively; median = 14). Seven of the subjects said it was hard to distinguish between the four different states related to the machine maintenance status based on the size of the flowers. One commented that adding more dimensions (increasing the number of sensors) would create a more complex visualization, making it harder to interpret. In general, though, these results indicated that the metaphor is readable.

All 12 subjects felt that interacting with BioAR was pleasant (five strongly agreed and seven agreed). Moreover, the participants thought that the representations of the machine states were esthetically pleasing (eight strongly agreed and four agreed). Eight felt more compelled to take care of a machine using the BioAR tree metaphor (two strongly agreed and six agreed), while four thought they would feel more engaged by a virtual pet (e.g., a cat or a dog). Three of the subjects wanted to be able to define their own metaphor, emphasizing the importance of freedom in defining the relationship between each sensor and its visual representation. Two participants mentioned that it would be interesting to include game concepts in the BioAR metaphor, promoting a competition between the machine's caretakers/users.

We measured the BioAR prototype's ease of use with the System Usability Scale (SUS). The device scored 71.25 points (median), which is above the average score of 68 obtained from 500 studies [3]. The SUS's learnability dimension also provided positive feedback. The participants felt they did not require technical support or need to learn a great deal to be able to use the system.

EXPERIMENT 2: SCALABILITY

This study aimed to verify whether BioAR could scale to a large number of machines, particularly with respect to perceiving visual changes. We intended the study to verify, through empirical evidence, that a great many devices can be encoded and that fast-changing states encoded with the BioAR metaphor elicit a preattentive response. We considered a task preattentive if it performed in fewer than 250 ms. We designed the study after Healey et al.'s work on preattentive processing of visual features [13]. In this respect, we investigated target-detection tasks with variations in form (a palm tree or a maple) and hue (red or green), as depicted in Figure 9.

The target-detection task simulated the search of a machine in need of maintenance while visualizing real-time data. In one task, 18 frames were displayed sequentially for a fixed exposure time of 100 ms (as in [13]). In our case, a frame contained 49 elements (7 × 7).

We organized the study as a within-participant experiment with the feature (hue or form) as the independent variable and the error as the dependent variable. Healey et al. studied the performance of visual features with two-dimensional (2-D) shapes and found that hue variations lead to fewer errors. Thus, we assumed that participants would make significantly fewer errors in the hue than in thew form condition.

PROCEDURE

There were 120 trials in each condition of hue and form, divided into 60 control trials and 60 experimental trials. One trial corresponded to one target-detection task. Only 50% of the trials had a target present (randomly determined). A target present appeared in only one of the 18 frames of the trial. We randomized the trial frame and the position of the target in the matrix. To ensure constant duration, we preloaded the 3-D scene for each trial.

A participant's task was to detect any of the following: 1) a red palm tree among green palm trees (hue/control); 2) a red maple tree among green maple trees (hue/control); 3) a red palm tree among green trees, half of them palm trees and half maples (hue/experimental); 4) a red palm tree among red maples (form/control); 5) a green palm tree among green maples (form/control); and 6) a red palm tree among maples, half of them red maples and half green maples (form/experimental).

Sixteen participants (12 males and four females) took part in the study, all with normal or corrected vision and no color-vision deficiency. In the experiment, a person stood in front of a tripod with a OnePlus phone facing the mockup factory model. We adjusted the height of the tripod for each subject, but the distance to the model was fixed.

We introduced the participants to the study with a written description that included the statement, "You have to detect the presence or absence of a machine that requires maintenance." After each trial, a dialog asked if the subject perceived the target to have been present (a yes-or-no answer). A feedback message stated whether the answer was correct or not. We provided a training phase of 16 trials for each experimental condition. Then the study began.

RESULTS

The hue condition counted 1,920 trials, with 66 wrong answers. The error mean in hue/control conditions 1) and 2) was 0.04 [standard deviation (SD) = 0.2], and the error mean in the hue/experimental condition 3) equaled 0.03 (SD = 0.16).

The form phase consisted of 1,920 trials, with 20 wrong answers. The error mean in form/control conditions 4) and 5) was 0.01 (SD = 0.08), and the error mean in form/experimental condition 6) equaled 0.01 (SD = 0.12). The experiment's error mean, considering both the hue and form trials, was 0.02.

We conducted a paired-samples t-test to compare the error means in the hue and form conditions. There was a significant difference in the hue condition scores (mean = 0.035, SD = 0.03) versus those of the form condition (mean = 0.01, SD = 0.021), with $t(31) = -4.52$ and $p < 0.001$.

CONCLUSION

This article presented a novel metaphor to bring a machine to life, as it were, representing sensor data that determined the machine's status in a nature-inspired metaphor, using features of a virtual tree. In a world with machines becoming increasingly complex, the metaphor we propose is a step toward compelling, calm interfaces.

Two studies support our assumptions that BioAR is understandable, compelling, and scalable. The first showed that the nature-inspired encodings are readable; that is, participants understood the status of the machine just from the BioAR metaphor. In this study, the subjects stated that they felt an urge to take care of the machine, thanks to the BioAR metaphor.

The second study showed that the metaphor scales to a larger number of machines (49) and changes regarding hue and form features are preattentively perceived. Contrary to our expectations, participants made significantly more errors with the hue condition than the form condition. Two explanations are plausible. Healey et al. experimented with shapes on a constant background. But the AR background interferes with the visualization, and, in the face of such interference, variations in hue are less differentiable than variations in form. The trees used in our experiment have arguably more complex shapes than the simple 2-D geometric shapes used in the original experiments. Furthermore, in terms of real-world experience, humans expect to see a tree change its aspect, but it is not common that a tree transforms into a different species. This discordance may have attracted early attention and caused early detection.

The results in both studies encourage us to continue exploring the BioAR nature metaphor as an innovative way to communicate real-time sensor information. Following this vision, a household full of IoT consumer electronics would communicate itself to its inhabitants as a beautiful garden. The BioAR nature metaphor can be applied to many other scenarios where multivariate real-time sensory data are available, e.g., in industry 4.0 plant floors, smart cities, and smart buildings in the areas of air pollution, traffic, energy consumption, and the like.

The studies helped us identify the following interesting avenues for research:

- Personalized encoding for the sensor data needs to be developed.
- We must address the issue that a large amount of sensor information integrated in a single visualization decreases understandability, especially when differentiating between intermediate states.
- A tree has only a few properties that can be used to encode sensory data. What are the limits of the metaphor?
- The connection between the BioAR nature metaphor and the IoT device needs to be improved (e.g., overlaying the BioAR onto the device and enhancing the interaction modalities).

We applied this metaphor so users could perceive the machine as a living being and, by doing so, learn to take better care of it. The act of caring for the machine rewards the user with an esthetic and pleasing tree, which enriches the user's environment. Moreover, we expect users' productivity and well-being to improve from contact with natural (or nature-like) elements [29]. We surmise that the metaphor positively reinforces the target behavior with a digital reward, which motivates the user to establish or strengthen the desired behavior. The first impressions of our study participants support this assumption.

To date, we performed two studies to validate the metaphor design, concentrating on the perceptual aspects of decoding information in a nature-inspired metaphor. However, there are other aspects of this metaphor that need to be explored. Our future work will address the issues of affect and quality of maintenance. In addition, we should consider the habituation issue, i.e., when the nature metaphor is introduced, users may feel engaged, but the effect could vanish as the novelty wears off. We intend to conduct a long-term study of participants' behavior to investigate our hypotheses.

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