Design Space and Usability of Earable Prototyping

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ABSTRACT

Earable computing gains growing attention within research and becomes ubiquitous in society. However, there is an emerging need for prototyping devices as critical drivers of innovation. In our work, we reviewed the features of existing earable platforms. Based on 24 publications, we characterized the design space of earable prototyping. We used the open *eSense* platform (6-axis IMU, auditory I/O) to evaluate the problem-based learning usability of non-experts. We collected data from 79 undergraduate students who developed 39 projects. Our questionnaire-based results suggest that the platform creates interest in the subject matter and supports self-directed learning. The projects align with the research space, indicating ease of use, but lack contributions for more challenging topics. Additionally, many projects included games not present in current research. The average SUS score of the platform was 67.0. The majority of problems are technical issues (e.g., connecting, playing music).

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in ubiquitous and mobile computing**.

KEYWORDS

earables; design space; problem-based learning; hearables

1 INTRODUCTION

The ear provides exciting opportunities for human-centered applications on the head as it combines multiple advantages to realize wearables [44]. Smart ear-worn devices can quantify the user and the world around them while naturally sitting in the ear canal (e.g., [19, 38]). Nevertheless, earables so far mostly required building custom hardware [3] or using platforms with restricted interfaces (see section 2), creating hurdles for non-experts. However, making the technology available to a broader audience might support innovation. A platform that aims to improve the availability of earable prototyping is *eSense* by Nokia Bell Labs [20].

We hypothesize that the eSense earbuds cover a research design space that we can structure and that it is available to non-experts in a self-learning assignment. First, our paper contributes a comparison of existing earable platforms. Based on 17 eSense publications, we propose a design space and verify it with seven articles of the other platforms. We then discuss usability when prototyping with eSense. We applied questionnaires and the system usability scale (SUS) and reviewed 39 undergraduate student projects.

2 RELATED WORK: EARABLE PLATFORMS

Plazak et. al. [33] reviewed the affordances of "hearables" and their possibilities for wearable computing. We focus on prototyping by inexperienced users with three requirements:

- demand no expertise in electronics or medicine
- have high-level, open data interfaces and frameworks
- require little to moderate programming experience

A platform already heavily used for problem-based education in various disciplines is *Arduino* [4]; however, building earables with Arduino requires substantial effort as wiring components, setting up connectivity interfaces, and fitting everything onto the ear is a challenging task already.

To summarize available earables, we initially *Google Search* "in-ear sensor" and "smart earbuds" and picked relevant results from the first 20 entries (earbuds with more than audio I/O). The rationale for choosing *Search* as opposed to, e.g., *Scholar*, was that market available earables are new and heavily commercialized. Table 1 presents our results. We then conducted *Google Scholar* based on the earable name and extract publications from the first 30 results (excluding patents / citations) that make use of any of the device capabilities.

Table 1: Earable comparison. (✓≙ yes, (✓)≙ limited, ✗≙ no) (API ≙ open app framework, FW ≙ open firmware, MIC ≙ microphone, SPK ≙ speaker, IMU ≙ inertial measurement unit, PPG ≙ photoplythysmography, TMP ≙ temperature sensor)

Platform	API	FW	MIC	SPK	IMU	PPG	TMP
cosinuss°	(✓)	✗	✗	✗	✓	✓	✓
Bose	✗	✓	✓	✓	✗	✓	✗
Soul Blade	✗	✗	✓	✓	✓	✓	✗
Jabra	✗	✗	✓	✓	✓	✓	✗
Bragi	(✓)	(✓)	✗	✗	✗	✗	✗
AirPods	(✓)	✗	✓	✓	(✓)	✗	✗
eSense	✓	✗	✓	✓	✓	✗	✗

Cosinuss° provides a highly engineered platform for medical applications with many sensors and multiple research publications [6, 10, 11, 18, 32, 37, 39]. However, data access requires proprietary software or unofficial, limited libraries. While the *Bose SoundSport* firmware is open, it lacks an application framework [7]. The *Jabra Elite Sports* have many sensors but no data access [17, 30], similar to *Blade* [12]. *Bragi* provides a powerful, closed developer framework but no more hardware [9]. Apple's AirPods have unofficial frameworks but not access to the IMU [2], similar to Google Pixel or Amazon Echo Buds. eSense [20], therefore, fills a critical gap for non-experts with a clearly defined, open framework with many research publications (see section 3). This simplification helps getting started with earables quickly.

Digression: On-Boarding new Technologies

A key motivation for making earables available to non-experts is to enable learning based on real-world projects. In that regard, the idea of problem-based learning (PBL) is to "*confront students with problems from practice which provides a stimulus for learning*" [8]. According to Munshi et al. [29], effective PBL should "*lead to thinking, analysis, and reasoning. It should stimulate self-directed learning and fit with students' prior knowledge. The problem should show clear links with the future profession and enhance interest in the subject matter.*". These underlying principles will guide our evaluation.

3 DESIGN SPACE OF EARABLE PROTOTYPING

Smart earpieces with, e.g., an inertial measurement unit [41], photoplethysmography [43], EEG electrodes [21], etc. enable a multitude of compelling use cases. We focus on eSense, which has been available for around two years at the time of concluding this paper. Using the paper by Kawsar et al. [20] and the *esense.io* website, we extracted seventeen peer-reviewed publications making direct use of the platform. In Figure 1, we extracted a preliminary proposal for a research design space with the primary motivation to use it for putting the non-expert projects into context. We verify that the seven publications based on other platforms presented in section 2 are also covered by Figure 1.
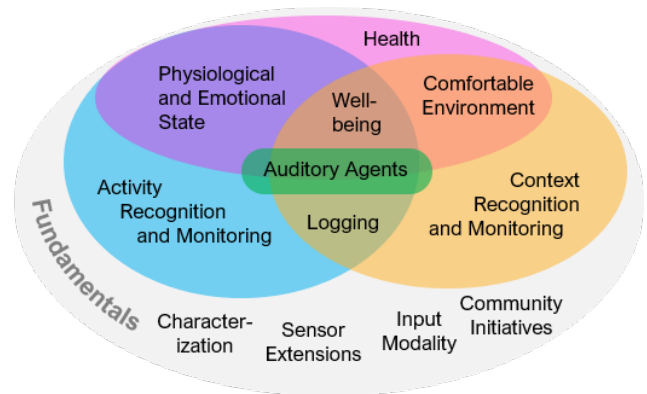

Figure 1: Initial design space characterization of publications on eSense to put into contrast with non-expert results.

In a *health* context, eSense was used to track the user's *physiological state* (respiration rate [38]). The platform was also used as mHealth building block [5] and to detect jaw clenching [40]. *Activity recognition* includes step counting [35], stay/walk detection as well as classifying speaking, eating and head shaking or nodding [15], drinking or chewing [23, 25], and exercising [16]. Additionally, frown and smile detection [22] as well as head movement [36] are possible indicators of the *emotional state*. Also, a data *logging* mechanism was proposed [14]. *Auditory agents* were used for auditive manipulation to support walking in a straight line [24]. Katayama et al. [19] proposed a setup for adapting a conversational agent's style, tone, and volume to the emotional, environmental, and social *context* to create a *comfortable environment*. *Well-being* creates a feedback loop, e.g., to understa conversational well-being [28]. In general, eSense can be an interface device of virtual conversational agents [1]. Work on *fundamental* principles creates the foundation of the research space. This includes e.g., *characterization* of wearing variability [27] and understanding earables as *input modality*, e.g., to control a robot arm [31]. *Community initiatives* include approaches for secure earable data sharing platforms [34], and also *sensor extensions* such as a magnetometer [13]. Publications for any of the other platforms also fall into the proposed prototyping design space.

4 THE ESENSE PROTOTYPING FRAMWORK

eSense is a stereo earable equipped with a microphone, 6-axis inertial measurement unit, and dual-mode Bluetooth. It allows recording of three real-time data streams - audio, motion, and proximity (BLE RSSI). It is powered by a CSR processor, has a 40 mAh battery, weighs 20 grams, and the dimension is 18 x 18 x 20 mm, including enclosure [20, 26]. Existing software libraries make it easy to get started with the earables. In our case, the students used the existing library [5] for *Flutter*, which is a cross-platform framework.

5 APPLICATION USE CASE PROJECTS

The objective of the application use case projects was to challenge individual students with developing a mobile app that makes use of the formerly introduced eSense framework.

Project Setup and Study Design

To initially support the students with starting their projects, we decided on the following project setup:

- all students fill in an initial questionnaire reporting general information and attitude towards earables
- we introduce the task, *Flutter* and the *eSense* library
- each student gets a pair of earbuds from our lab
- students independently implement their projects
- hand in the result and fill in a second questionnaire

Otherwise, we did not limit students to any idea or particular challenge and asked them to build a creative solution that uses any of the features provided by the framework.

Results

In total, 70 students participated in building individual projects. Out of all students, 63 were male and seven female. Sixty-eight participants were undergraduate computer science and two business informatics students. 22 took the university's HCI lecture. Twenty-four students never built a mobile app before, and only five used Flutter. Twelve have used Bluetooth before. Fifty-eight students reported never having heard of earables, before we introduced them in the survey.

Suitability for Problem-based Learning. The questions we asked build upon related work on PBL [29]. Figure 2 illustrates the results of four rating scales that users filled in before the project. Overall, there is no agreement if earables are relevant for the future profession or match the overall curriculum. Key factors might be different electives and individual career plans of students. Nevertheless, the majority of students agree that the project is interesting, therefore supporting to get into the subject matter.
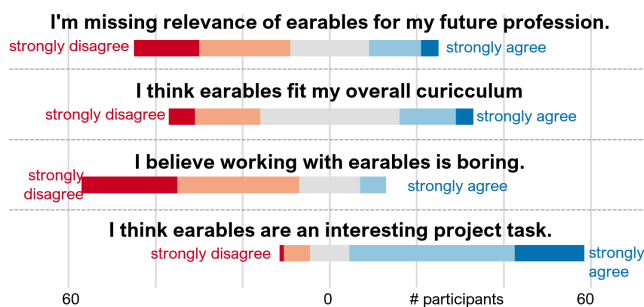

Figure 2: Rating scales filled-in by students (n = 70) before building projects with the eSense framework.

Retrospective Project Reflections. Unfortunately, due to COVID-19, we could only complete the retrospective questionnaire for 37 students. We report the results of the rating items in Figure 3. Overall, the project has supported self-directed learning as students strongly agree that it improved their knowledge about earables, app development, and Bluetooth Low Energy. Even though the earables did not entirely work without problems and errors occurred regularly for some, the assignment is fun. The task was not frustrating for the majority of students and Figure 5 gives further insights on problems that occured.
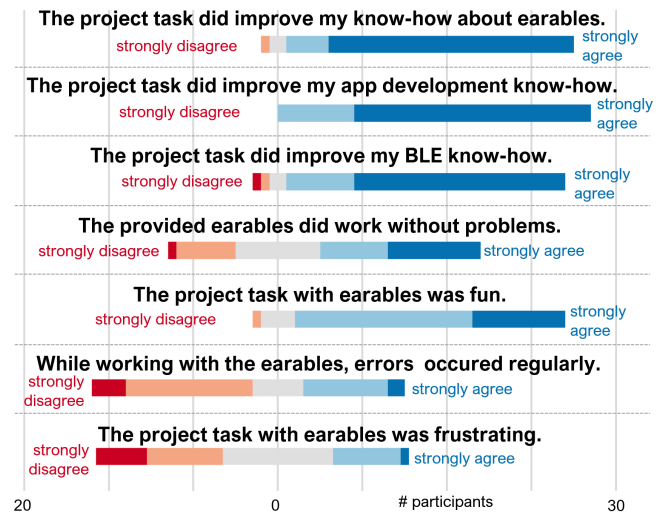

Figure 3: Results of self-directed eSense projects (n = 37).

Figure 4 reports the project types according to the categories defined in section 3. A topic not found in the design space analysis were games, for which earables served as direct input. Also, students built activity tracking (e.g., push-ups, situps, squats, walking, cycling, street-crossing, headbanging) with threshold state machines. One person classified nodding with ML. Auditory agents solely used text-to-speech. Some students implemented physiological state tracking (e.g., sleep position and work desk body pose). The auxiliary material contains detailed project descriptions.
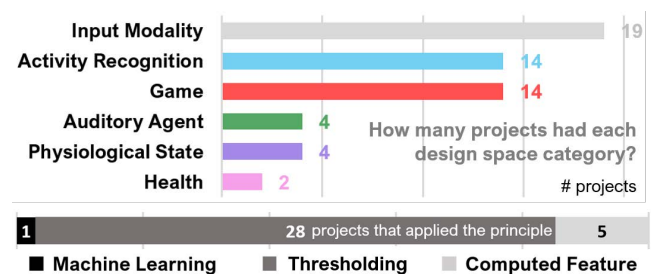

Figure 4: Project results based on category and data processing approach (n = 37). Projects can have multiple categories.

Likely due to the higher complexity, no project included context recognition (e.g., use proximity, or audio features).

The overall mean SUS score was 67.0 (max: 90.0, min: 35.0, sd: 14.2), which, according to literature, is close to the average reference value of 68 [42]. For good usability, however, the score should be above 80. In Figure 5, we present the problems that users faced extracted from free-text.
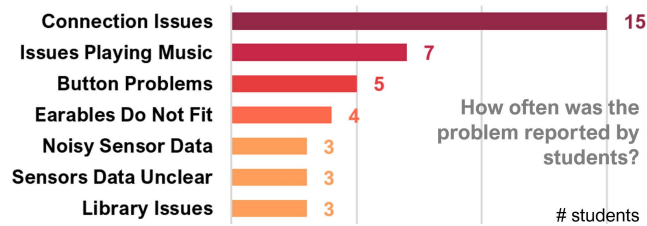

Figure 5: Problems during development extracted from free text provided by participants (n = 37).

Connection issues included earables taking long to connect and problems connecting both earbuds. Seven users had problems with unstable audio. Issues with the button occurred when it involuntarily triggered music, started phone calls, or sent more than one press. Especially projects with more movement reported loose fit. Only three users reported trouble understanding sensor data. Issues with the library (iOS inconsistencies) and noisy data are also very little. In contrast to the technical problems, students expressed that "the earables look modern", that it was "the best assignment they had at university so far" and also "an interesting introduction into pervasive computing". Overall, all students successfully fulfilled the assignment. Even though the complexity of results varies, eSense was easy to use by non-experts.

6 BLUETOOTH LIBRARY PROJECTS

To further understand the PBL-usability of eSense, we let another group of students implement a Bluetooth library.

Project Setup and Study Design

The project and study setup was as follows:

- students gather requirements and design software
- build a Bluetooth library and sports tracking for eSense
- fill in a retrospective questionnaire about the project

Results

We recruited two teams of five students, whereas nine students voluntarily filled in the questionnaire that we sent them after project completion. They were are all undergraduate students in their second year in computer science. Both teams implemented a Bluetooth library successfully and one is available as NuGet package[1] for *Xamarin*. Interestingly,

[1] https://www.nuget.org/packages/EarablesBLE/

for the items presented for the other project condition in Figure 3, we observe a similar trend, so we do not report them separately. However, we asked additional questions regarding the documentation of the low-level Bluetooth interfaces provided by eSense. The results are illustrated in Figure 6. Overall, the students had little trouble understanding and processing the earables' data, and also the documentation was sufficient, making eSense a good candidate for learning the fundamentals of BLE GATT.
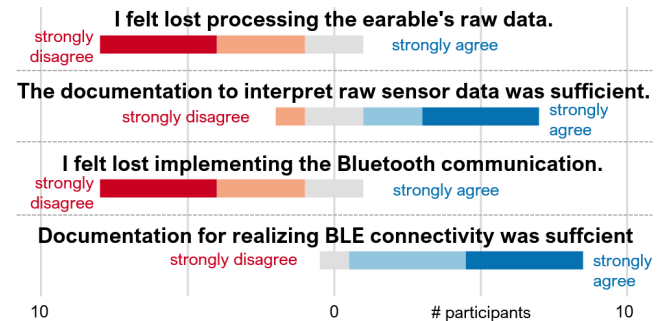

Figure 6: Rating scale results of the students implementing low-level Bluetooth libraries (n = 9).

The SUS score for the second project setup type was not significantly different with 70 (min: 30, max: 82.5, sd: 16.44). The challenges that had to be overcome by the students also align with issues with connectivity and playing music.

With an allotted time frame of six months and five students per team, the final use case results closely match the shorter project assignments. Thus, the Flutter communication library significantly improves development speed.

7 LIMITATIONS

The initial design space that we present in our paper will likely expand in the future. Also, we did not precisely assess the time that students spent working on their solutions or if students neglected an initial idea because it was too complex.

8 CONCLUSION AND FUTURE WORK

Overall, earables are enablers of a broad research design space. Undergraduate CS students are excited about the subject matter and enjoy as well as succeed in building applications with the prototyping platform eSense. However, relevance for their future career is limited. Frustration mostly roots in technical issues and little problems are reported with realizing ideas. The platform's documentation for teaching in a PBL setting seems sufficient. Considering the limited technical depth of student projects, teachers should encourage responsible design (i.e., in a health context). The reference material might also include core sensor concepts, and classification libraries could simplify prototyping.

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